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DESIGN AND DEVELOPMENT OF A SEGMENTED MAGNET HOMOPOLAR TORQUE CONVERTER

C. J. Mole, et al

Westinghouse Electric Corporation

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DESIGN AND DEVELOPMENT OF A SEGMENTED MAGNET HOMOPOLAR TORQUE CONVERTER

Semi-Annual Technical Report for
Period Ending May 31, 1973

Submitted to ARPA in June, 1973

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13. ABSTRACT

This program is for the research and development of a new mechanical power transmission concept: the segmented magnet homopolar torque converter. The purpose of this device is to convert unidirectional torque of constant speed (such as from a steam turbine prime mover) into variable speed output torque in either the forward or reverse directions. The concept offers an efficient, lightweight low volume design with potential application over a wide range of speeds and power ratings in the range from hundreds to tens of thousands of horsepower. This machine concept can be applied to commercial and military advanced concept vehicles for both terrain and marine environments.

The program places particular emphasis on the materials technology of liquid metal current collection systems for the reason this is essential for the success of the homopolar machine concept.

This report period encompasses the completion of Phase I study phase, and the initiation of Phase II experimental work. In Phase I the technical problems were reviewed, the machine concepts were studied, and a detailed technical plan was evolved for the entire program. In Phase II, theoretical, engineering, and experimental tasks will be performed to develop a reliable current collection system which will be demonstrated in an actual segmented magnet homopolar machine, and a design layout evolved for a demonstration torque converter.

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SECTION 1

INTRODUCTION AND SUMMARY

1.0 GENERAL

This is the second semi-annual technical report and covers the work performed from December 1, 1972 through May 31, 1973. During this period, the Phase I workscope was completed, and Phase II initiated.

1.1 BACKGROUND

This is a new program for the research and development of a new Westinghouse proposed mechanical power transmission concept: the segmented magnet homopolar torque converter (SMHTC). The purpose of this device is to convert unidirectional torque of constant speed (such as from a steam turbine prime mover) into variable speed output torque in either the forward or reverse directions. The concept offers an efficient, light-weight low volume design with potential application over a wide range of speeds and power ratings in the range from hundreds to tens of thousands of horsepower. Initial analysis indicates that this machine concept can be applied to commercial and military advanced concept vehicles for both terrain and marine environments over a wide range of applications with considerable benefit to the U.S. Government, provided the complex current collection, liquid metal technology, and materials problems can be completely solved.

The present contract is part of a proposed three phase program to develop the segmented magnet homopolar torque converter (SMHTC). This program will, a) solve all of the problems relating to current collection systems for segmented magnet machines; b) demonstrate the solution of the problems in a small segmented magnet homopolar machine (SEGMAG); c) utilize the technology in the development to design, construct and test a segmented magnet homopolar torque converter (SMHTC).

The program will place particular emphasis on the materials technology of liquid metal current collection systems for the reason this is essential for the success of the homopolar machine concept, for high power density applications.

1.2 OBJECTIVES

1.2.1 Summary of Objectives

In Phase I, completed on January 9, 1973, all of the technical problems were reviewed, the machinery concepts studied, and a detailed technical plan was evolved for the entire program.

Phase II has the primary purpose of providing the necessary theoretical and engineering design work, as well as the supporting experimental tasks, to develop reliable and efficient subsystems necessary for the successful operation of segmented magnet homopolar machines. Key task areas include, (a) the design, construction and operation of a SEGMAG machine; and (b) evolving a design layout of a demonstration torque converter (SMHTC).

The objectives of Phase III will be to extend the technology developed in Phase II for constant speed machines (such as generators) to the case of a torque converter which operates at low speed, zero speed, or reversing conditions, and then to construct and test a demonstration SMHTC.

1.2.2 Summary of Technical Tasks

The technical subtasks for Phase I were described in detail in the first semi-annual technical report (E.M. 4471), and are as follows:

1) Segmented magnet homopolar torque converter (SMHTC) system studies.
2) Application study.
3) Liquid metal current collection systems.
4) Materials study.
5) Segmented magnet homopolar machine design.
6) Seal study.
7) Plan for phase II

There are five major task areas under Phase II:

(1) Machine Design and Testing

A segmented magnet homopolar machine (rated 3000 HP, 3600 rpm) will be designed, constructed, and tested. This development will prove the concept and allow testing of improvements for the SMHTC such as the current collectors, seals, and materials. Extensive testing will be conducted.

A homopolar generator will be obtained from the General Electric Co. (GEC) of England. The prime purpose is to obtain operational experience with GaIn as a current collector liquid. This machine's mechanical and electrical design and performance will be studied as a basis for evaluating presently used models for predicting machine performance.

(2) Application Studies

Several of the applications resulting from the Phase II application studies will be reviewed in conjunction with ARPA, and the most useful applications for segmented magnet homopolar machines or torque converters will be selected.

(3) Current Collection Development

The purpose of this task is to evolve an effective liquid metal current collection system and to evaluate its performance. The principal areas of study concern handling, containment, removal of contaminants, and measure of power losses.

(4) Liquid Metal Support Systems

The purpose of this task area is to develop, design, fabricate, and instrument a liquid metal recirculation loop and a cover gas recirculation system to provide maximum protection to the liquid metal in the current collector region. Both the liquid metal and the cover gas will be recirculated for contaminant removal and purity maintenance. Consideration will be given to use of these systems for removal of waste heat from the machine.

This task includes a compatibility study of all machine materials (insulation, lubricants and structural materials) with the liquid metal current collection fluid.

A fundamental studies program is part of this task area and is concerned with those aspects of liquid metal technology that are necessary to optimize the current collection electrodes to provide long term reliability for stable current conduction. Topics include surface wetting by liquid metals, aerosol formation, corrosion or alloying reactions, effect of high current transfer, and chemistry control in liquid metals using soluble getters.

(5) Seal Study

In this task seal systems will be developed to, (a) confine the liquid metal to the collector zone; and (b) prevent air contamination of the liquid metal and loss of its protective cover gas atmosphere. Test rigs will be constructed to simulate actual machine operating conditions.

1.3 SUMMARY OF CURRENT PROGRESS

1.3.1 Machinery

1.3.1.1 segmented magnet homopolar torque converter (SMHTC)

Two SMHTC concepts, based on segmented magnet homopolar (SEGMAG) machines, were developed. They will be capable of transmitting energy from a 3600 rpm prime mover to a propeller shaft whose speed varies from a forward speed of 200 rpm to a reverse speed of 200 rpm.

Additional studies were initiated to evaluate other SMHTC configurations with initial efforts aimed at reversible homopolar motors.

1.3.1.2 segmented magnet homopolar machine (SEGMAG)

The SEGMAG machine design was essentially completed. Critical items were defined and procurement action initiated to maintain program schedule.

1.3.1.3 GEC machine

This generator (rated 16,000 amperes short circuit, 8 volts open circuit emf) has been ordered from GEC Ltd. Shipment is scheduled for October 1973. Provision of the necessary utilities is being made for its installation, and a laboratory site has been allocated.

1.3.2 Application Study

No work was scheduled for this task in the current period.

1.3.3 Liquid Metal Current Collection Systems

Based on a state-of-the-art review and an analytical study, NaK-78 was selected as the best liquid metal fur current collectors employed in SEGMAG type homopolar machines. GaIn was selected as the alternate choice. NaK-78 is compatible with most machinery structural metals, copper, and insulation materials.

Quantitative analysis of the complex electro-magnetic interactions which will be experienced by functioning current collector systems indicated the following conclusions:

- Preference for "unflooded gap" liquid metal current collection systems (based on a necessity to reduce ordinary viscous and MHD power losses).

- Power losses in the liquid metal of "unflooded gap" current collectors used in machines of the SEGMAG design concept will be relatively small (less than one per cent of the machine's output). Low power loss is achieved because of the small contact area with the liquid and because the ambient magnetic fields are weak.

- A serious concern in applying an "unflooded gap" liquid metal current collection system is confinement of the liquid to the annular gap of the current collector. Centrifugal force tends to keep the liquid metal in the gap, whereas gravity and magnetic forces tend to expel it. In the case of generator applications, loss of liquid metal via aerosol formation is considered a serious problem because of excessive surface turbulence associated with high speed operation.

An experimental program was developed with the prime objectives resolving problems associated with the application of liquid metal current collector systems in SEGMAG type homopolar machines. The initial concern centers on an ability to control liquid metal flow rates into and out of the collector over a wide range of machine operating conditions. Other equally important concerns include techniques for confining liquid metal to the current collector and the long term performance reliability of liquid metal in the face of continuous viscous working and transfer of electrical current loads.

Experimental apparatus capable of testing liquid metal current collectors under simulated machine operating conditions was designed and is being fabricated. A current collector design will be developed and finally tested in the SEGMAG prototype demonstration homopolar generator.

1.3.4 Liquid Metal Support Systems

Candidate materials which will be utilized in the SEGMAG demonstration machine were selected and prepared for NaK compatibility studies. The test plan and acceptance criteria to qualify the candidate materials for use in a NaK environment were also defined. The apparatus necessary to carry out the NaK compatibility studies was set-up and calibrated. Experimental work has commenced with the preparation of rotor bar insulation systems and the preliminary screening of candidate seal materials. In addition, a literative survey was conducted to select braze materials that are compatible with NaK.

Design of the liquid metal and cover gas sub-systems to service the prototype segmag generator are near completion. Initial test programs were conducted to prove design concepts and evaluate equipment performance. Procurement of components and support equipment for the generator was initiated.

NaK support system activities have progressed with the design, construction, and calibration of small electro-magnetic flowmeters; design and fabrication of an oxide cold trap to purify recirculating NaK; procurement of a recirculating, two column, inert cover gas purification unit; and design and construction of the instrumentation stand for the current collection tests. Ongoing studies in the areas of liquid metal level detection in the current collector during operation; decontamination and safety practices; and chemical means of establishing wetted surfaces in NaK are continuing.

1.3.5 Seal Study

A study of various shaft seal concepts has indicated that a tandem circumferential seal offers considerable promise as a rotor shaft seal for the prototype SEGMAG machine. The function of this seal is two-fold: (1) it confines the dry, inert cover gas to the machine's containment vessel; (2) it prevents contamination of the containment vessel by both air as well as the oil used in lubricating the support bearings. A test rig was constructed to evaluate the performance of tandem circumferential seals with respect to seal wear and gas leakage. Test seals suitable for operation on a 3 inch diameter shaft can be tested over a 3600 rpm speed range in a dry nitrogen environment. Reversing capability, jogging, and dynamic braking were designed into the variable speed drive system.

Conventional carbon-graphite materials lose their lubricating ability in an inert, no-moisture environment. In view of this fact, the ability of the seal material to retain its self-lubricating ability in the machine's environment is of major interest. For this reason, compatibility study program complements the seal test program. Candidate seal materials are being evaluated with regard not only to their compatibility with the dry, nitrogen environment of the machine but also to their compatibility to the liquid metal used in the current collector.

1.3.6 Phase II Plan

A plan for the 18-month Phase II program was detailed, and documented. The workscope is proceeding accordingly. This plan describes all of the tasks that are deemed necessary to solve the technical problems identified in Phase I for producing a demonstration of feasibility with a 3000 hp segmented magnet homopolar generator by the end of Phase II. Investigations include current collector development, liquid metal and cover gas systems, seal studies, materials studies, machine design, and evaluation tests.

SECTION 2
MACHINERY

2.1 SEGMENTED MAGNET HOMOPOLAR TORQUE CONVERTER (SMHTC)

2.1.1 Objectives

The objective of this program is to investigate a 30,000 HP torque converter capable of transmitting energy from a 3600 rpm prime mover to a propeller shaft whose speed varies from a forward speed of 200 rpm to a reverse speed of 200 rpm. This concept will be demonstrated with a conceptual design producing 6000 HP at 200 rpm from a 1200 rpm drive unit. The output shaft shall deliver constant torque from zero to 200 rpm in forward and reverse direction. The concepts demonstrated in this machine will be extrapolatable to the larger unit.

2.1.2 Prior and Related Work

The SMHTC concept was derived from a unique modular DC homopolar machine being investigated at Westinghouse. This machine, known as a segmented magnet homopolar machine (SEGMAG) uses series-connected DC modules to obtain the design output.

2.1.3 Current Progress

The electrical analysis of the large (30,000 HP) and small (6000 HP) machines were completed. The electrical analysis for the large unit was performed to determine the approximate size and weight for the unit. Two conceptual designs (radial and axial) are being prepared for the 6000 HP machine.

The radial SMHTC design uses a segmag generator mounted within a segmag motor. The design uses a stationary stator located between the rotating drive shafts. The stator is separated magnetically to prevent interaction of the excitation from the motor and generator portions of the machine. The conceptual design layout for the radial design was prepared.

The axial design uses an inline segmag generator and motor. This design is feasible if high current buses from the generator to the motor can be limited to approximately 12 inches. Design layouts were prepared for this concept. A design study was initiated to develop alternate SMHTC concepts. The initial thrust of this study is to evaluate concepts for a reversing homopolar motor.

2.2 SEGMENTED MAGNET HOMOPOLAR MACHINE (SEGMAG)

2.2.1 Objectives

The objective of this program is to demonstrate the SEGMAG concept used in the SMHTC and to provide a test vehicle for evaluation of the current collection systems, containment seals, and liquid metal handling systems developed in previous subassembly testing. The demonstration unit (rated 3000 HP, 3600 RPM) will subject the current collectors to current densities, leakage flux and other conditions associated with operation in a machine environment. In addition, the unit will provide for long-term testing of current collectors, their attendant support systems and the machine itself to develop operational data for liquid metal machines.

2.2.2 Prior and Related Art

The SEGMAG concept was developed to provide a high performance DC machine without requiring superconducting magnet excitation. This low reluctance machine, using room temperature excitation, has capability for high output per unit weight and volume. The modular construction allows for higher outputs by using many modules connected in series. The characteristics of this machine have been investigated thoroughly in another U. S. Government Contract (NOOO 14-72-C-0393).

2.2.3 Current Progress

The electrical and mechanical design of the SEGMAG demonstration unit was essentially completed. A detailed design layout is being developed to permit generation of subassembly detail drawing. The electrical design analysis was completed with the exception of the field excitation coil which is in the final design phase. The rotor critical speed analysis and machine stress analysis are nearing completion. The final machine design allows for maximum flexibility in the areas of current collection, containment seals and liquid metal support systems. Ease of assembly and decontamination during disassembly were also considered. The major design factors were:

- <u>Machine Assembly</u> - The original SEGMAG configuration placed the excitation coils behind the current collectors. This required that the stator be assembled from several subassemblies. This procedure would require extremely tight tolerances to insure alignment of the rotating and stationary portions of the current collectors. An alternate design was evolved that allowed the use of a two piece stator consisting of an axially split cylinder. This configuration places the field coils between the stator current collection sites

enabling assembly of the coils and rotor into the lower stator half. This concept allows machining of the assembled stator as a unit enabling precise alignment of current collectors. In addition, the collector clearances can be inspected upon installation of the rotor and field coils into the low stator half. The assembly is completed by installing the upper stator half with a seal between the two halves. Although this configuration results in a larger rotor, the three piece construction provides advantages during assembly, disassembly and decontamination.

- Rotor Construction - The rotor design is strongly dependent upon the collector configuration developed during subassembly testing. The initial rotor design provided for crossover in the rotor for series connection of the modules. In order to allow the flexibility of accommodating a variety of potential collector configurations rotor crossovers were abandoned. In their place, three separately fabricated modules will be used. The rotor conductors and current collector rings will be assembled into the iron structure for each of the three modules and the rotor assembled. The rotor collector rings will be left unmachined until the selected configuration is determined in mid-November of 1973. This design will permit concurrent efforts in machine design and current collector development resulting in shortened program schedules.

- Stator Lead Connections - The electrical leads for the machine will be connected on the outside of the stator. These external connections will increase the weight and volume of the machine; however, they will provide the testing flexibility necessary for a prototype machine. The external connections will allow no-load, single module and rated output operation during the test program.

- Containment - The containment design provides for primary and secondary vessels to prevent external leakage and internal contamination. The primary containment seals the machine internals while the secondary vessel prevents leakage from machine primary barrier from escaping into the atmosphere. Both areas will be provided with an ultra-dry inert atmosphere. The primary containment vessel penetrations will be hermetically sealed using highly reliable mechanical joints and welded seals where possible. The secondary vessel will contain the piping connections for liquid metal, cooling fluid and purification gas cooling and liquid metal piping will require insulating sections to

prevent excessive leakage current within the machine. This multiplicity of connections will require access for potential maintenance and repair during the test program. For this reason the secondary containment vessel has been designed for maximum accessability.

- Materials - Samples of candidate insulating, sealing, and structural materials have been made available for NaK compatibility testing. An attempt is being made to keep the machine design flexible enough to accommodate those required materials changes which may result from the compatibility test program, while avoiding an overly complex machine configuration. The selection of a NaK-compatible braze material, for example, might require a high brazing temperature which could reduce the strength of the rotor iron and of the copper of the conductor bar/collector ring assembly. Therefore design modifications to include steel support rings are being investigated for the copper structures, and a center module which can be shrunk onto the shaft after brazing, is being considered.

- Thermal Design - A cooling tube imbedded in the stationary part of the current collector assembly serves as the heat sink for the collector test stand. The cooling requirement for a single collector has been calculated to be about 4 kw at 3600 rpm. This is predominantly due to viscous drag of the liquid metal filling the collector gap.

  The cooling system has been designed with the ability to use either a light transformer oil or water as the cooling medium. Oil is planned for most of the testing at low and moderate collector speeds. At the high speed range (above 3000 rpm) the switchover to water will take place in order to provide the necessary thermal performance.

  Potentially critical procurement items have been identified. These include the rotor forgings, collector rings, hollow conductor for the field winding, and the stator iron. Procurement action has been initiated on these items.

2.3 GEC GENERATOR

2.3.1 Objectives

The General Electric Company, Ltd., of England has developed an experimental homopolar generator which utilizes a GaIn current collection system. This generator employs an electrochemical purification system to maintain the purity of the liquid metal and avoid the "black powder" problems of previous investigators who used this metal. ARPA has approved purchase of this generator for experimental evaluation under the contract. The machine will be used to provide operating and technical experience with GaIn as a current collector liquid and to supplement the main experimental studies which will be conducted with NaK. This experience is expected to be valuable in broadening the scope of the program beyond the alkali metals. The physical design of the machine and its performance will be investigated thoroughly, and the unit may also be employed as a high current dc source in the current collector test program.

2.3.2 Prior and Related Work

Liquid metal current collection systems have a high potential to function efficiently with long, trouble free life in the face of high electrical current loads and high rotational speeds conceived for homopolar machines of the advanced segmented magnet design.

Based on extensive study, NaK-78 was selected as the best liquid metal for current collectors employed in the Segmag machine, and GaIn was selected as the alternate choice.

Since GaIn has been identified as the back-up choice to NaK, the ability to work with and study a functioning GaIn unit is expected to be highly instructional in the general sense and also to shorten any subsequent development effort with GaIn.

Based on an extensive search of the market we have concluded that the GEC machine is the best vehicle to provide the GaIn experience needed for this program. No other liquid metal machine in the world, to our knowledge has operated longer than 40 hrs without maintenance. Therefore, this machine, which has operated up to 1000 hours with no problems, represents a unique development.

2.3.3 Current Progress

The generator was ordered from GEC in April 1973 and is scheduled for delivery in October 1973.

Performance testing of prototype units were reviewed with GEC personnel by Westinghouse (Dr. E. Berkey), during April 1973 visit to England.

An installation site has been selected within the Westinghouse R&D Center. Steps are being taken to prepare the site, install the necessary utilities, and to provide the drive motor.

SECTION 3

APPLICATION STUDY

3.0 OBJECTIVES

Review and select promising applications for the segmented magnet homopolar machines and torque converters.

Several of the applications resulting from the Phase II application studies will be reviewed in conjunction with ARPA, and the most useful application will be selected.

3.1 PRIOR AND RELATED WORK

The Semi-Annual Technical Report for Period Ending November 30, 1972 discussed in some detail a number of applications which are potentially feasible. All applications are contingent upon proper solution to the problem of current collection. The use of liquid metal to transmit simultaneously large quantities of electrical current and large quantities of heat flow from the rotating armature must be solved in a reliable and safe fashion to realize these applications. While considerable progress has been made during Phase I of this study, such progress has been relevant to the basic research involved with such a current collection system. The current collector must now be tested (in Phase II) in its expected environment, i.e., the conduction of heat and current in the prsence of magnetic field phenomena.

3.2 CURRENT PROGRESS

No work was scheduled for this reporting period.

SECTION 4
CURRENT COLLECTION SYSTEMS

4.0 OBJECTIVES

The major objectives of this Task are: 1) to identify preferred current collector designs by analytically investigating the complex electromagnetic interaction and forces which will be experienced by functioning collector systems under a variety of operating conditions and liquid metals, 2) to develop an experimental program leading to solutions of problems associated with the application of liquid metal current collection systems as established from the state-of-the-art review and analytical study, 3) to design, fabricate, and assemble test apparatus suitable for carrying out the experimental work, 4) to evolve current collector designs based on results of the experimental work suitable for homopolar generators employing the SEGMAG concept, and 5) to fabricate and evaluate the collector designs under prototypic SEGMAG generator operating conditions including rotational speed, ambient magnetic fields and electrical load currents.

4.1 PRIOR AND RELATED WORK

To function with low power loss and long life under continuous operating conditions at high electrical loads and high rotational speeds, liquid metal current collection systems are judged to have a higher potential for success than those employing solid-type brushes. Current collectors employing liquid metal as the contact medium are capable of transferring very high levels of current efficiently because essentially all of the contact area is actively engaged to transfer current.[1-3] A state-of-the-art review has confirmed, however, that serious problems remain to be solved before successful long-term operation of homopolar machines utilizing liquid metal current collection systems may be achieved.

The feasibility of employing liquid metal current collectors in powerful homopolar machines requires that the liquid metal be confined to thin ring-shaped volumes or annular channels comprising the current transfer or collection zones of the machine. This requirement is based on a necessity to reduce prohibitively high hydrodynamic power losses which otherwise occur in systems wherein the liquid metal completely fills the machine's internal gaps or void spaces. Such reduction in hydrodynamic power loss is directly achieved through significant limitations in "wetted" contact area.[4] Additional reduction in power loss is obtainable by minimizing the ambient magnetic field intensity in the current collection zones.[5] Power losses in the liquid metal of "unflooded gap" current collectors used in homopolar machines which employ the SEGMAG design concept will be relatively small. Low power loss is achieved because of the small contact area with the liquid metal and because the ambient magnetic

fields in the current collection zones are very weak.

Probably the most serious concern in applying an "unflooded gap" liquid metal current collection system is confinement of the liquid to the annular gap of the current collector. The systems are designed so that centrifugal force tends to keep the liquid metal in the annular gap of the current collectors. This constraining force is opposed by several forces which tend to remove liquid metal from the collectors.[6-7] The significant opposing, or expelling, forces are classified as gravity, acceleration, and magnetic. The balance between the constraining and expelling forces will depend on the type and specific design of the machine. Since a generator will always be running at high speed, its relatively high constraining force will be helpful in obtaining confinement of the liquid metal. Motors must operate at both low and high speeds, even zero speed, and thus the confinement problem is of much greater concern in that case.

An important concern involving the reliability of liquid metal current collection systems over long time operation is if low electrical resistance within the fluid and low contact resistance at the collector member surfaces can be maintained. Both of these concerns appear to be associated with purity or integrity of the liquid metal, especially in the face of viscous working. Of concern, with regard to volume resistivity, is a change of state phenomenon which has been shown with certain liquid metals.[7-8] Such transfer in the physical state is manifested by the collector fluid changing to a "powder". Unclean collector surfaces, initially or subsequently formed, may seriously inhibit "electrical wetting" and lead to increased contact resistance with the liquid metal.

4.2 CURRENT PROGRESS

During the current period, progress was made in the analytical study of power losses, liquid metal confinement, and other considerations in the selection of liquid metal for current collectors useful to SEGMAG machines. Additionally, our experimental program was developed to resolve recognized problem areas in applying liquid metal current collectors. Experimental test apparatus was designed and fabrication initiated. Preliminary current collector designs were made and fabrication of these is underway. Detailed information is contained in sections 4.2.1 through 4.2.6.

4.2.1 Power Losses in Current Collectors

Although significant improvements in current collection efficiency are achieved through the unflooded machine gap designs, power losses are still significant, and warrant detailed study.

Principal types of power loss are listed below.

1. Ordinary hydrodynamic losses.
2. Magnetohydrodynamic (MHD) losses due to circumferential magnetic force on the liquid metal.
3. Eddy current drag.
4. Ohmic losses due to the load current crossing the collector gap.

Ordinary Hydrodynamic Losses. These power losses occur due to shear in the liquid metal caused by relative motion of the inner and outer portions of the collectors. For many configurations under consideration, the Reynolds number is quite high and the Hartmann number is low, so the flow will generally be turbulent. Losses in this case tend to be proportional to the density of the liquid, the cube of the rotor surface speed, the wetted area, and a friction factor which is a weak function of the Reynolds number.[4,9-11] To keep this loss to a minimum, a liquid with a low density should be used, the wetted area should be kept to a minimum, and the linear speed of the rotating portion of the collector should be kept as low as possible.

MHD Losses. The influence of ambient magnetic fields in the current collection zone, occasioned by the machine's excitation, depends on the relative magnitudes of their axial and radial components. The axial magnetic field component, B_x, if present, will interact with the orthogonal radial electrical load current density, J_y, to create circumferentially directed Lorentz body forces, F_θ, in the liquid metal; see Fig. 4-1. This force may be in either direction, depending on direction of the vector quantities, so it may either increase or decrease the velocity of the liquid metal.

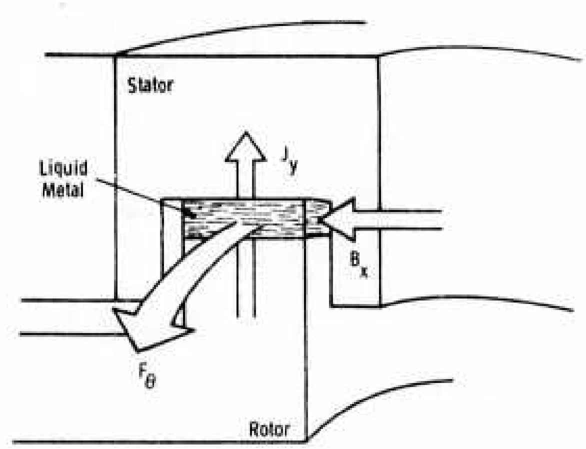


Figure 4-1 - Interaction Between B_x and J_y in Liquid Metal Producing Circumferentially Directed Body Force, F_θ

Generally, a circumferential force in either direction will increase the total power loss of the system. In the case of a motor, with the field coils located on the stator, the force is usually exerted in the direction of rotation. For a generator, with the field coils located on the stator, the force is exerted in the direction opposite to the direction of rotation. If a generator and motor are compared with all parameters affecting power loss the same, except for the polarity of the load current (or of the field applied to the armature), the total power loss will be the same. Equations relating the total power loss per unit area of collector surface are extracted from Ref. 5 and represented below.

$$P_{av} = \frac{f \rho V^3}{8} \left[1 + 3 \delta^2\right] \qquad (1)$$

when

$$\delta = \frac{2 B_x J_y d}{f \rho V^2} < 1,$$

$$P_{av} = \frac{f \rho V^3}{8} \left[2(1 + \delta) \sqrt{2\delta - 1}\right] \qquad (2)$$

when

$$\delta > 1,$$

where:

P_{av} = viscous loss per unit collector area

f = Fanning friction factor

ρ = fluid density

V = rotor surface velocity at the collector

δ = collector parameter

B_x = axial magnetic field

J_y = collector output current density

d = collector radial gap

The circumferential Lorentz body forces influence the fluid power losses in two ways. First, by distorting the fluid's velocity profile, they modify the shearing stresses normally induced hydrodynamically by the moving contact member. The shearing stresses are increased in the case of a generator, but decreased for a motor. Consequently, fluid hydrodynamic power losses are increased in the former case, but decreased in the latter; see Fig. 4-2. In the motor situation, when values of the collector constant (δ) are greater than 1, the mean fluid velocity is greater than the rotor speed. Under these conditions, the fluid contributes useful torque to the motor and the hydrodynamic losses are negative, or power is gained from the fluid. Second, by modifying the fluid's mean velocity, the Lorentz forces affect the electrodynamic losses. The moving fluid, in the presence of an axial magnetic flux, will act as an electrical generator or motor connected in series with the homopolar machine. For relatively low Lorentz forces, $\delta<1$, the effect is to decrease the electrodynamic losses in a homopolar generator, but to cause an increase in a motor. When the Lorentz forces become high, when $B_x \times J_y$ is large or $\delta>1$, electrodynamic losses increase for both machine applications. The net effect of increasing axial magnetic field components and radial current densities in the collector fluid zone is to increase the power losses.

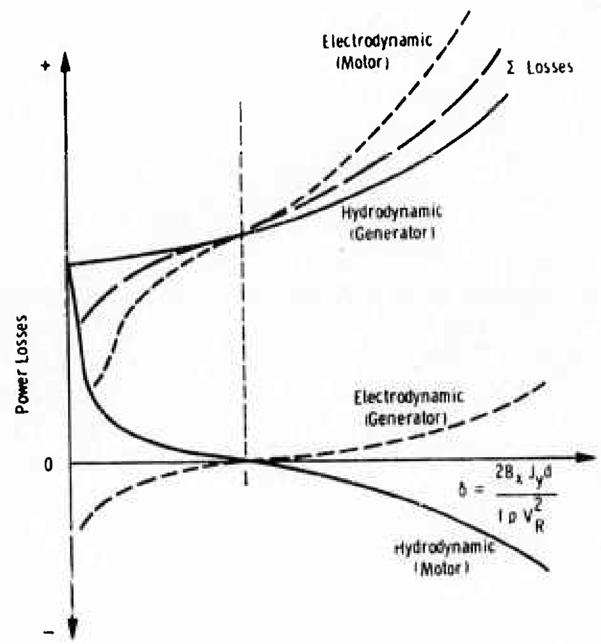


Figure 4-2 - Liquid Metal Power Losses

Eddy Current Drag. Another cause of power loss is due to eddy currents caused by a magnetic field with a component normal to the conducting surface of the collector rotor. The case of a radial magnetic field and axial rotor surface is illustrated in Fig. 4-3. The velocity of the

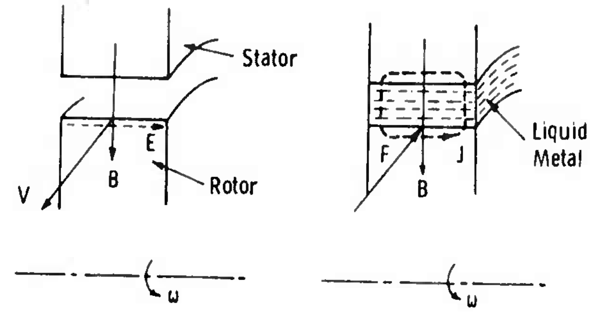


Figure 4-3 - Eddy Current Drag on Rotor

rotor (V) interacts with the field (B) to generate an electric field (E) in the rotor. This causes a current of density (J) to flow around the circuit shown. The interaction between this current and the radial magnetic field produces a force (F) on the rotor. This force is opposite in direction to the tangential velocity of the rotor, and therefore causes a loss of mechanical power. Although the loss is manifested as mechanical drag on the rotor, its cause is electrical in nature.

A simplified analysis shows that this eddy current loss will be significantly greater than the previously discussed hydrodynamic and electrodynamic power losses, when B_y and B_x magnetic fields of comparable magnitudes are individually considered. If comparable B_y and B_x magnetic field components are simultaneously present, however, the circulating eddy currents and associated power losses will be greatly reduced in magnitude.[12]

Ohmic Losses. Another type of power loss is due to the electrical resistance of the liquid metal through which the load current flows. This may be calculated directly from the conductivity of the liquid metal, the thickness of the collector gap, the area through which the load current flows, and the magnitude of the load current. This loss is usually much smaller than the MHD power losses discussed above. This loss may be reduced by using a high-conductivity liquid metal, a small gap, and a large area.

Calculated power losses for collectors with relatively weak axial leakage fields of 0.03 Tesla typical of SEGMAG homopolar machines, are presented in Table 4-1.

The combined viscous and ohmic power losses shown are based on assumed design SEGMAG machines and for three different collector fluids. The data indicate that GaIn leads to the highest power losses and NaK, the lowest. In either case, however, total losses represent a small percentage (<1%) of each machine's power output.

TABLE 4-1
CALCULATED CURRENT COLLECTOR POWER LOSSES*

	SEGMAG	SMHTC			
	3,000 HP Generator	6,000 HP Generator	6,000 HP Motor	30,000 HP Generator	30,000 HP Motor
Collector Radius, (meters)	0.17	0.25	0.58	0.28	1.42
Collector Gap, (meters)	0.76×10^{-3}	1.59×10^{-3}	1.59×10^{-3}	1.59×10^{-3}	1.59×10^{-3}
Load Current, (amperes)	10^5	10^5	10^5	10^5	10^5
Current Density (amperes per square meter)	6.2×10^6	6.2×10^6	3.2×10^6	6.2×10^6	3.1×10^6
Rotor Speed (revolutions per second)	60	20	3.3	60	3.3
POWER LOSS PER COLLECTOR,** (Watts per square meter)					
Collector Fluid					
NaK-78	1.66×10^5	0.47×10^5	0.09×10^5	7.19×10^5	0.24×10^5
BZ-73***	3.22×10^5	0.80×10^5	0.14×10^5	12.4×10^5	0.39×10^5
GaIn-76	12.9×10^5	1.60×10^5	0.13×10^5	50.9×10^5	1.19×10^5

*Magnetic induction normal to load current 0.03 Tesla
**Viscous plus ohmic power loss
***Composition is 73 w/o Cs metal with the balance NaK-78.
This liquid metal has a melting point below 0°C (i.e., Below Zero).

In the case of machines with high magnetic fields (superconducting windings), high load current density, and low rotor speed calculated values of collector power losses, not shown, present GaIn as a more attractive liquid metal than NaK. For other assumed operating conditions, NaK is generally superior to GaIn. Even so, collector power losses are significantly high for both liquid metals when employed in machines which impose high magnetic fields in the current collection zones.

4.2.2 Liquid Metal Confinement Problems

Probably the most serious problem of an "unflooded gap" liquid metal current collector system is confinement of the liquid to the annular gap of the current collector, and exclusion of the liquid metal from the remainder of the machine rotor-stator gap. It is especially necessary to prevent the liquid metal from forming a continuous path from one collector to the next, since in unflooded gap machines, the adjacent collectors are generally at different voltages.

The collectors are designed so that centrifugal force tends to keep the liquid metal in the annular gap of the current collectors. This force is opposed by several forces which tend to remove liquid metal from the collectors. In a horizontally mounted machine, at low rotational speed, gravity tends to cause liquid metal to flow around the collector ring from the top to the bottom. It may overflow at the bottom into the space between adjacent collectors and cause a short circuit. At somewhat higher speeds, the liquid metal tends to pool at the top, where it loses speed. In this case, also shorting of adjacent collectors may occur.

There are also magnetic forces which tend to remove liquid metal from the current collectors. The most significant of these is due to the machine load current which flows along the armature conductors, and crosses the gap at the current collectors.[6-7] The load current produces a magnetic field which runs circumferentially around the axis of the machine. The model shown in Fig. 4-4 illustrates the load current, and the magnetic field it produces. The induced field, when interacted with the load current, produces a body pressure which tries to expel the fluid axially out of the collector gap.

If all the current crossing the gap travels along armature bars toward the right, and no other current threads the collector rotor ring, the axial body pressure which tends to more liquid metal through the gap is given by the equation:

$$P = 6.28 \times 10^{-7} \, I_p^2 \qquad (3)$$

Newtons per square meter. I_p is the load current per unit of collector perimeter, amperes per meter.

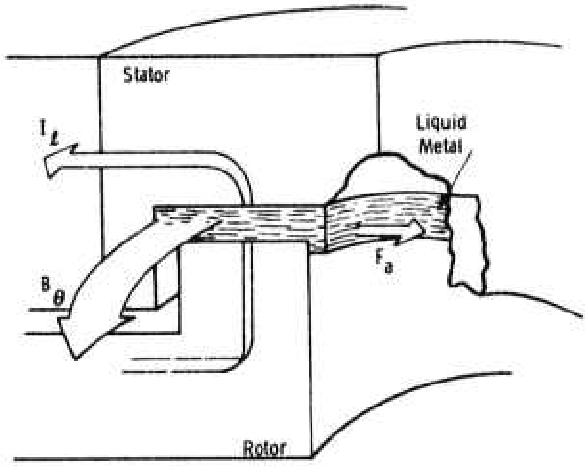


Figure 4-4 - Interaction Between B_θ and I_ℓ in Liquid Metal Producing Axially Directed Body Force, F_a

If the load current is reversed in direction, the magnetic field due to it also reverses, so the force on the liquid metal is unchanged in either magnitude or direction.

In some machine designs, alternate armature conductors are at different voltages, and they are attached to separate collectors. In these designs, the current carried by one set of conductors may pass through the ring of the collector under consideration without crossing its gap. The axial pressure across that collector will then be greater than the value given by Eq. (3). For example, if the current passing through the collector ring is equal to the current crossing it, then the pressure will be three times as great.

The effect of the load current-magnetic force is to cause liquid metal on the sides of the rotating collector member to assume unequal heights. When the machine speed is sufficiently high, a relatively small degree of fluid height inequality will automatically occur, which provides a hydraulic pumping force that just balances the opposing magnetic force; see Fig. 4-5.

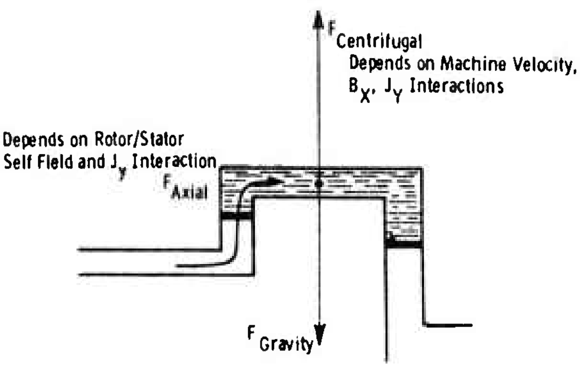


Figure 4-5 - Forces Acting on Liquid Metal

Under conditions of low machine speed or standstill and a partially filled collector, where load current per unit of collector perimeter will likely be greater than normal, rather high axial magnetic pressures will be developed. Even short periods of operation under these conditions, with little or no hydraulic pumping counterpressure available, will seriously challenge the ability to confine liquid metal to the current collection zone. This condition, rather than current density, may define the maximum load current capability of liquid metal current collectors.

Another effect which tends to remove liquid metal from the collector gap is the phenomenon of aerosol formation. Very small droplets are ejected from the free surfaces of the liquid metal, presumably because of turbulence, surface waves, etc. These tend to form a deposit on adjacent surfaces. Presumably, the solidity is due to the particles becoming coated with a thin oxide layer, so they do not combine and run back into the collector as a liquid.[7-8]

To provide some numerical examples to illustrate the relative significance of the effects described above (excluding aerosol formation), calculations were made for the hypothetical SEGMAG machines. Results of these calculations are given in Table 4-2. Calculations were made for NaK-78. The centrifugal force is presented to provide a measure by which the various forces which tend to remove liquid metal can be compared. The centrifugal force is calculated by assuming that the speed of the liquid metal is one half that of the rotor, which is typical for the case in which relatively weak magnetic leakage fields exist and in which both rotor and stator surfaces are equally smooth. The centrifugal force is calculated for a collector in which the radial dimension of the liquid metal is 0.01 meters. The centrifugal force is then presented as a pressure.

The effect of gravity is calculated as the pressure needed to keep the liquid metal from dropping downward by moving radially inward at the top of the rotor. For this calculation, it is assumed that the radial extent of the liquid metal is 0.01 meters. The effect of gravity is also calculated for liquid draining around the circumference of the collector from top to bottom. In this case, the static pressure due to a column of liquid metal with a height equal to the full diameter of the rotor is calculated.

The pressure due to the load current is calculated from Eq. (3). It is assumed in all cases that the load current is 100,000 amperes. It is assumed that all of the current passes through the collector under consideration.

4.2.3 Additional Considerations in Selection of Liquid Metal

The utilization of liquid metal current collection fluids, although resolving several critical electrical problems in homopolar machines, introduces a new technology and increased complexity to machine design.

TABLE 4-2
PRESSURES* DUE TO VARIOUS EFFECTS IN CURRENT COLLECTORS
(NaK-78 Collector Fluid)

Machine	3,000 HP Gen.	6,000 HP Gen.	6,000 HP Motor	30,000 HP Gen.	30,000 HP Motor
Collector Radius, (meters)	0.165	0.254	0.584	0.280	1.42
Rotor Rotational Speed, (radians per second)	377	126	21	377	21
Pressure Due to Centrifugal Force on 0.01 meter	50,500	8,690	555	86,000	1,350
Pressure Due to Gravity on 0.01 Meter	84	84	84	84	84
Pressure Due to Gravity Across Rotor Diameter	2,780	4,280	9,840	4,720	23,900
Pressure Due to Load Current of 100,000 Amperes	5,840	2,460	470	2,030	80
Pressure Due to Changing Field Excitation	10	16	36	17	88

*Pressures given in Newtons per square meter.

Not only must an optimal liquid metal be selected, but now complex support systems such as purification loops, cover gas systems, and compatible materials must be considered.

Property Considerations. Ideally a liquid metal for current collector application should possess the following properties:

1. It should remain in the liquid phase for all expected machine temperatures.

2. Its density, viscosity, and electrical conductivity should be such that they result in low power losses.

3. Its surface tension should be high to resist changes in shape and position.

4. Its specific heat and thermal conductivity should permit temperature control.

5. It should have adequate and enduring wetting characteristics.

6. It should be non-toxic, chemically stable, and resistant to contamination.

7. It should be compatible with selected contacting materials, i.e., con-corrosive and non-erosive.

8. It should be safe and easy to handle.

Unfortunately, no one liquid metal is known to possess all of these desired properties. As shown in Table 4-3 and as demonstrated in Table 4-1, NaK-78 is a prime current collector fluid. NaK-78 is a eutectic alloy of sodium and 78 wt% potassium.[13-14] GaIn 76 is also a prime candidate, but cannot be considered as highly as NaK-78 since it is corrosive to structural metals, copper, and transition metals; may cause liquid metal embrittlement in structural metals;[15] has a higher melting point and density; and for most applications envisioned causes higher hydrodynamic losses than NaK-78.

Feasibility of NaK-78. NaK-78 is chemically reactive with the normal atmospheric constituents oxygen, carbon dioxide, and water vapor, and must be protected by a high purity, inert cover gas such as nitrogen. Alkali metal protective cover gas systems are well developed and are commercially available. Maintenance of NaK purity and the prevention of oxide crusts should be feasible with current technologies. NaK is compatible with most structural metals, copper, and other transition metals.[16] Also, NaK handling, pumping, containment, and purification are documented technologies with a proven history. NaK oxides are easily removed from machine surfaces with methanol and water and leave no residue.

TABLE 4-3
PHYSICAL PROPERTIES OF SEVERAL LIQUID METALS

	Hg	Hg-In	Na	NaK-78	GaIn-76	BZ-73
Melting Point (°C)	-38.9	--	97.8	-12.5	15.7	-76.0
Density (kg/m^3) x 10^{-3}	13.6	10.0	0.930	0.850	6.30	1.480
Viscosity (kg/m·s) x 10^3	1.2	1.5	0.69	0.47	1.5	0.62
Surface Tension (N/m)	0.48	--	0.195	0.115	--	0.093
Conductivity (mho/m) x 10^{-6}	1.0	1.0	10.0	2.17	3.45	1.41

4.2.4 Experimental Program

An experimental program leading to the solution of problems associated with the application of liquid metal current collection systems as established from the state-of-the-art review and analytical study has been prepared. The technical plan involves experimental investigations to resolve potential problems in regard to (1) injection and withdrawal of liquid metal from the current collector, (2) stability of liquid containment in the collector annular gap, (3) retainment of liquid metal chemical integrity in the face of viscous and electrical working, (4) axial expelling force due to load current, and (5) development of liquid metal confinement methods. A description of the experimental task areas follows:

1. Injection, Quantity Control, and Withdrawal of Liquid Metal

Because the liquid metal under consideration (i.e., NaK-78) will react chemically with any oxygen and water vapor present in the ambient cover gas, it is necessary to provide means for removing the reaction products from the liquid before their accumulation becomes excessive. It is anticipated that this will be done by withdrawing liquid metal from the current collector, circulating it through a purification system, and returning it again to the collector. Means must be provided for injecting liquid metal into the current collector without causing excessive turbulence, for controlling the amount of liquid metal in the annular gap, and for withdrawing liquid metal from the current collector. Initial experiments are intended to develop these means and capability.

2. Demonstration of Containability

Fluid volumes are easily distorted or made to flow when influenced by unbalanced forces. Experiments will be made to evaluate various effects which tend to remove liquid metal from the collector gap. The phenomenon of low speed drop-out will be evaluated for several collector geometries. Tests at speeds higher than the drop-out speed will also be made to determine whether a film of liquid metal tends to flow down the stator channel due to the lack of centrifugal force in the thin boundry layer in contact with the stator surface. Tests of brief duration at high speed will be run, and observations will be made to determine whether any unexpected phenomena occur which tend to remove liquid metal from the collector gap.

3. Long-Term Viscous/Joule Effects-Liquid Metal Integrity

The purpose of these experiments is to determine whether changes in current collector performance may occur when the liquid metal is simultaneously subjected to high levels of viscous working and electrical currents over long periods of time. Performance may be affected by the production of aerosols, loss of liquid metal conductivity due to impurities, and erosion of the collector surfaces. Tests of extended duration will be made at

speeds up to the highest anticipated for the prototype SEGMAG machine. A radial magnetic field will be applied to the collector to generate a very large eddy current in the liquid metal. This condition will simulate the load current and serve to reveal any unknown effects associated with the load current which may remove liquid metal from the collector gap.

4. Load Current Expelling Force

The tendency for load current-self magnetic field forces to remove liquid metal from the collector gaps, and the effectiveness of centrifugal force in providing for retention of liquid metal, will be evaluated. A description of these forces and an indication of their magnitudes were previously presented in Sec. 4.2.2. Axial pressure caused by the load current forces will be simulated by providing a gas pressure differential across the collector gap. Various techniques for retaining liquid metal in a current collector gap against such axial pressures will be evaluated. Considerations of methods for minimizing the effects of load current will also be made.

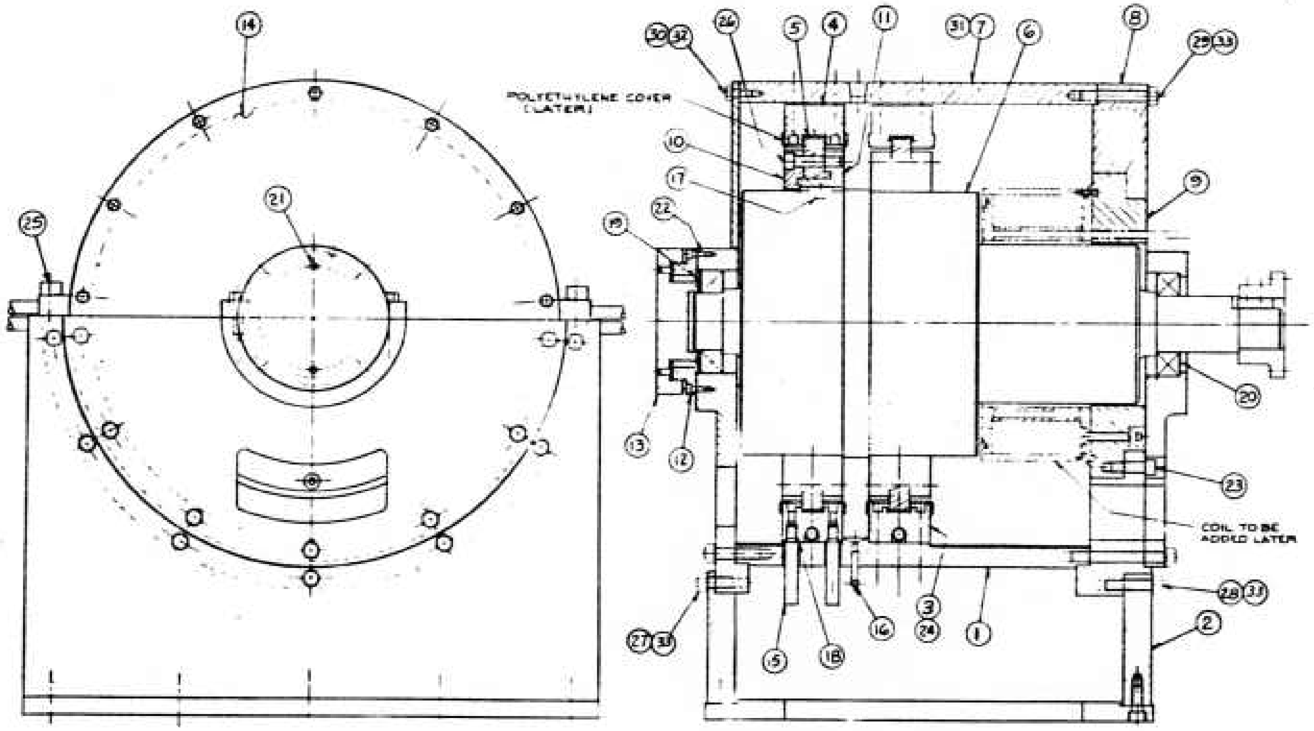
5. Liquid Metal Confinement Methods

A major objective of the long range experimental program is to provide current collectors in which liquid metal can be confined to all speeds, including standstill. Certain methods for confining the liquid metal to the current collector when run under a variety of conditions will be tested. The confinement systems will be subjected to forces of thy same magnitude as those anticipated in the prototype SEGMAG. Results from this work will provide design criteria for current collectors which provide for liquid metal confinement under all operating conditions, including the SEGMAG and torque convertor (SMHTC).

4.2.5 Experimental Test Apparatus

Experimental apparatus capable of testing liquid metal current collectors under the operating conditions discussed in the Technical Plan has been designed and is being fabricated. A view of the general assembly drawing of the current collector test stand is shown in Fig. 4-6. The test stand is relatively simple in design, flexible in test usage, and easily assembled.

The basic test stand provides for testing two current collectors in combination or separately, as desired. To facilitate the testing of different collector designs, the rotors are readily attached to a specially shaped drive shaft with clamping rings. The rotor diameter and maximum rotational speed were selected to be similar in size and value to those anticipated for the prototype SEGMAG demonstration machine. The mating collector test stators or shrouds are fabricated as half cylinders and they are supported and surrounded by a similarly shaped, but longer outer



Item	Description	Part No.	Qty
1	SGT HSG SUB ASSY	[illegible]	1
2	BASE SUB ASSY	[illegible]	1
3	BOT COLLECTOR SHROUD	[illegible]	2
4	TOP COLLECTOR SHROUD	[illegible]	2
5	COLLECTOR	[illegible]	2
6	SHAFT	[illegible]	1
7	TOP HOUSING	[illegible]	1
8	TOP BACK PLATE	[illegible]	1
9	COIL PLATE	[illegible]	1
10	CLAMP RING	[illegible]	1
11	SUPPORTING RING	[illegible]	1
12	BRG ADJ RETAINER	[illegible]	1
13	BRG ADJUSTER	[illegible]	1
14	TOP COVER	[illegible]	1
15	TUBE	[illegible]	2
16	.500 OF [illegible] x .035 WALL SST TUBING		
17	3/16 x 1.00 WOODRUFF KEY		2
A 18	O RING [illegible]	[illegible]	32
B 19	BELLEVILLE SPRING	[illegible]	2
C 20	BEARING	[illegible]	2
21	.250-20 x .50 LG SOC SET SCR CUP POINT		2
22	.190-32 x .50 LG SOC HD CAP SCR SST		6
23	.375-16 x .75 LG SOC HD CAP SCR SST		8
24	.375-16 x 1.00 LG SOC HD CAP SCR SST		4
25	.500-13 x .50 LG SOC HD CAP SCR SST		[illegible]
26	.375-16 x .75 LG SOC HD CAP SCR SST		[illegible]
27	.375-16 x 1.00 LG HEX HD SCR SST		[illegible]
28	.375-16 x .75 LG HEX HD SCR SST		[illegible]
29	.375-16 x 2.00 LG HEX HD SCR SST		[illegible]
30	.250-20 x .75 LG HEX HD SCR	SST	7
31	.250 DIA x 1.00 LG DOWELL PIN	SST	4
32	.250 DIA LOCKWASHER MED	SST	[illegible]
33	.375 DIA LOCKWASHER MED	SST	[illegible]

Figure 4-6 - Current Collection Test Stand

housing member. During certain experiments this outer half-cylinder housing can be removed to afford accessibility to and good observation of the test collectors. Removal of the top housing is possible because the whole test stand, excluding the drive motor and the drive transmission, will be contained in a gas tight glove box. Provisions were made for filling the glove box with high purity nitrogen gas and for maintaining it at a pressure slightly above that of the test room. For other experiments, ports are provided in the end housings for partial indirect viewing of the current collectors.

Provisions were made so that a variable radial magnetic field can be obtained in the test collector zone for certain experiments, to generate very large electrical eddy currents in the liquid metal. This is accomplished by surrounding a portion of the specially shaped test stand shaft with an electromagnet coil and through proper selection of magnetic and nonmagnetic materials for the end housing members. The coil was designed to provide a maximum test magnetic field intensity (0.1 Tesla) five times as great as that expected in the SEGMAG prototype machine (0.02 Tesla). A 15 hp, 1750 rpm, dc motor was selected to meet the drive power and torque requirements imposed by the eddy current drag and viscous power losses anticipated in the test collectors. The test stand will be driven through a 2:1 step up pulley-belt transmission. A magnetically loaded-gas buffered rotating contact type seal was selected to prevent room air leakage into the glove box through the drive shaft penetration.

A number of stainless steel and copper tubes are provided for introducing and withdrawing liquid metal into and from the test current collectors, for circulating coolant fluid in and out of the collector stators, and when desired, for introducing gas to create pressure differentials across the collectors.

Most of the technical plan objectives can be met with this test stand. A collector design will be evolved and subsequently evaluated in the SEGMAG prototype demonstration homopolar generator. This will permit the final test program to be run under prototypic operating conditions. Upper levels of the test parameters to be imposed during the final current collector experiments are presently envisioned to be 80 meters per second rotor speed, 0.03 Tesla axial magnetic field, and 80,000 amperes load current.

4.2.6 Current Collector Design

Flow of liquid metal directly into and out of the collector annulus is envisioned to be a serious problem. The problem is one of how to control precisely the liquid metal flow rate through the collector under all machine operating conditions. Variable centrifugal pressure acting on liquid metal in the gap, caused by changes in rotor speed and/or load current, introduces a variable counter pressure to the inflowing fluid

and also provides a variable exit pressure to the outflowing fluid. This situation requires that careful regulation of the liquid metal injection pressure be provided, compensating for the effects of changing machine operating conditions, to prevent the possibility for either under (starvation) or over (flooding) filling of the collector annular gap. Both of these conditions are undesirable. In the first case the machine may be open-circuited and in the second case liquid metal may be lost from the collector, possibly causing short circuiting of the machine.

A possible solution to the variable centrifugal pressure problem is to introduce freshly purified liquid metal into the collector gap at or near the free surface of the residing liquid metal. In similar fashion, the effluent liquid would also be withdrawn from the perpetually constant-pressure free surface. One method useful for achieving such actions is to employ inlet and exit sump-weir arrangements. Preliminary experiments employing this technique in conjunction with a small current collector (0.11 meter diameter rotor) have been quite successful, especially in regard to coping with under and over-fill injection situations. Two collectors, differing in geometrical shape, have been designed to accommodate this technique and are being machined for initial experimental evaluations in the large test stand.

Collector designs are also being formulated to accommodate the effects of asymmetrical fluid heights on the rotor sides, anticipated to be caused by load current forces. Other collector designs are being considered for the radial magnetic field-power loss experiments. The interim current collector experimental program involving two smaller test stands is continuing. The experiments are being directed toward testing collector geometrical shapes and liquid metal handling and flow schemes.

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SECTION 5
LIQUID METAL SUPPORT SYSTEMS

5.0 OBJECTIVES

The objectives of this Task are: 1) to investigate the compatibility of candidate machine materials with NaK and GaIn as well as with potential decontamination solutions, 2) to perform literature, analytical, and experimental studies to identify suitable materials and suggest alternate choices where necessary, 3) to design, fabricate, and test the liquid metal loop and cover gas systems that will be required in the SEGMAG generator, and 4) to establish the operating parameters and interactive responses of these systems.

5.1 PRIOR AND RELATED WORK

The compatibility of machine materials, both organic and inorganic, with the liquid metal current collection fluid and cover gas were reviewed in the literature and analyzed by chemical composition. Consideration was also given to the reaction products which would be generated during machine cleanup and decontamination. Even though many of the materials were found to be compatible with the proposed liquid metal current collection fluid, they were ruled out simply because of their incompatibility with these reaction products. In the event that total materials compatibility cannot be achieved, alternate methods were studied such as the canning or encapsulation of those component materials which may be reactive with the liquid metal or the decontamination products. In addition, the canning or encapsulation would be expected to prevent insulation outgassing products from reaching the liquid metal. This was considered to be a far more important consideration than the liquid metal leaving the current collection region and coming in contact with the interior of the machine.

Proposed methods of liquid metal handling and purification, as well as the required on-line instrumentation to monitor the chemistry of the liquid metal were reviewed. This included the liquid metal loop system and the requirements necessary to interface the liquid metal/cover gas system with the machine current collector. In addition, the requirements for machine cleanup, routine operation, and safety were analyzed.

The liquid metals proposed for use as current collection fluids in advanced design homopolar machines are sodium potassium alloys (NaK) and gallium-indium alloys (GaIn). These metals, depending on their composition, may be liquids at room temperature (25°C). For this particular application, NaK_{78} (eutectic) is the prime candidate current collection fluid. GaIn has been considered, but due to the higher power losses associated with it and to its strong corrosive action on structural

metals, it is only secondary as a candidate fluid. Because NaK is so reactive, an inert cover gas is necessary to prevent oxidation of the liquid metal alloy. High purity nitrogen may be used in this application although other gases such as argon or helium may be considered.

Once the current collection fluid and cover gas were defined, the machine was studied from a total materials compatibility point of view, since many components were expected to be in contact with both the liquid metal alloy and also the cover gas. Materials compatibility problems may result from many areas. A few of those considered are listed below:

(1) Liquid metals reacting with materials,

(2) Materials outgassing and contaminating the liquid metal,

(3) Local machine hot spots,

(4) Impurities in the cover gas contaminating the liquid metal.

Assurance of continuous on-line operation of a liquid metal current collection system required investigation from the standpoint of maintenance of liquid metal purity. Of the various methods of preventing liquid metal contamination, the following were selected as most reasonable for machine application: (1) Fabricate the machine from the standpoint of high vacuum technology to prevent serious outgassing of oxygen and moisture to the liquid metal current collector region; (2) Utilize a positive pressure gradient inert cover gas inside the machine housing to prevent the entrance of atmospheric contaminants (oxygen, moisture); (3) Continuously recirculate the cover gas through a purification cycle; (4) Continuously recirculate liquid metal from the current collector region through a purification loop. Total system contamination control can be expected through currently available technologies.

Integral gas purification/machine/liquid metal loop system variables were considered with respect to system interacting, startup, operation, and shutdown problems, safety, decontamination practices, and instrumentation. As a result of these considerations, no potential problems were viewed as insurmountable.

A number of homopolar machines are now in operation which utilize both NaK and GaIn as current collection fluids. The cleanup and decontamination procedures which are currently being utilized are adequate for most situations which are now encountered. In general, more problems are encountered with NaK than with GaIn but the procedures to handle these problems were reviewed and were found to be fairly well defined. Methods which are now employed utilize alcohol, alcohol/water, and live steam to safely react and decontaminate NaK systems. In utilizing these procedures a number of hazards are involved. These

include liquid metal exposure to personnel, the evolution of hydrogen as one of the reaction products and the caustic liquids which result from the cleanup procedures. From visiting a number of homopolar machine sites which employ NaK as the current collection fluid, the most hazardous problem appears to be that of hydrogen generation and the possibility of explosions which exist under decontamination conditions.

5.2 CURRENT PROGRESS

5.2.1 Material Selection and Compatibility

The principal task for Phase II has been to define machine materials that are compatible with NaK, the liquid metal current collection fluid. Proposed materials are to be subjected to the liquid metal environment, decontaminated, and evaluated as a function of embrittlement, pitting, electrical measurements, and physical and chemical changes.

Candidate materials for construction of the SEGMAG demonstration machine have been defined; these include rotor bar insulation, coating and potting compounds, silastic sealants, banding pads and tapes, laminates, seal materials (dry lubricants), braze alloys, structural metals, and cooling fluids.[1] Table 5-1 lists all proposed machine materials which are being evaluated in the program by exposure to NaK and NaK decontamination fluids. In addition, the evaluation criteria are also listed for each material. A test plan has been established and the apparatus necessary to perform the experiments has been installed and calibrated.

Experimental work has been initiated with the selection and preparation of rotor bar insulation. Test specimens were prepared in accordance with accepted state-of-the-art methods for insulating large electric machines. Hard drawn copper bars served as the base material. Kapton film was 1/2 lapped on the bar and subsequently covered with a mica-kapton (1/2 lapped) tape or mica glass tape. An outer binder tape (1/2 lapped) was then applied. This system was then cured for 6 hours at 150°C. After the cure cycle, the rotor bar insulation was vacuum pressure impregnated with an epoxy resin and cured at various time/temperature intervals. Four different rotor bar insulation systems have been prepared. Figure 5-1 illustrates the initial preparation of a rotor bar system. An example of a complete insulation test system including the test canister is shown in Figure 5-2. Note that the four different rotor bar insulation systems are all potted in a silica filled epoxy compound which permits the testing of the various systems in a single canister. The test plan requires that these test specimens be subjected to an NaK environment for various time/temperature intervals.

Preliminary screening experiments have been performed to evaluate seal and dry lubricant materials for NaK compatibility. These short term experiments were performed at room temperature (25°C) in NaK with a cover gas of high purity nitrogen. To date, eighteen of the nineteen

Table 5-1. Candidate SEGMAG Materials to be Evaluated for NaK Compatibility

Material	Phase/Form	Evaluation Criteria
Rotor Bar Insulation	solid-total insulation package	weight (gain/loss), hardness, embrittlement, electrical resistivity
Coating-phenolic-alkyd paint	film on steel substrate	weight (gain/loss), adherance (bend 90°, peel) embrittlement, pitting
Potting compound 53841-MU silica filled epoxy	cast solid	weight (gain/loss), discoloration, embrittlement, pitting
silastic sealants (1) 116 RTV (2) 732 RTV	cast solids	weight (gain/loss), discoloration, embrittlement, pitting, geometrical changes, outgassing (components/amounts)
Banding Pads	stiff tape	weight (gain/loss), hardness, embrittlement, discoloration, outgassing (components/amount)
Banding Tapes (1) polyester on glass (2) acrylic modified epoxy on glass (3) polyester on experimental fibers	stiff tape	weight (gain/loss), hardness, embrittlement, discoloration, outgassing (components/amount)
Laminates (1) Glass cloth base, silicone resin (2) Glass cloth base, epoxy basin	solid	weight (gain/loss), delamination, resistivity, pitting, discoloration
Seal Materials (1) 90 WGI,5Ag,5CaF_2 (WGI-A) (2) 80 WSe_2,20GI (WGI) (3) C/Graphite $\bar{w}$ MoS_2 (SK235 and SK278) (4) EVC Graphite (5) 80WSe_2,20GI with oxide coat (WGI-O)	solid	weight (gain/loss), pitting, geometrical changes, hardness

Table 5-1 (cont'd.)

Material	Phase/Form	Evaluation Criteria
(6) C/Graphite with resin binder (SK-218)		
(7) Pure WSe_2		
(8) CR-218		
(9) CR-219		
(10) MF343 (Bronze 1 Graphite)		
(11) 1257 C/Graphite		
(12) Boron Nitride + 3 w/o Boric Oxide (BN-O)		
(13) Impervious Pyroimpregnated Graphite (LEM-2)		
(14) Raython Pyrographite (LEM-1)		
(15) High Density Graphite		
(16) AXZ Poco Graphite (d - 1.5g/cc)		
(17) AXM Poco Graphite (d=1.8g/cc)		
(18) AXF Poco Graphite (d=1.9g/cc)		
(19) ATJ Graphite		
Braze Alloys (1) soft solder (copper and copper & nickel plated) (2) silver solder (3) nicrobraze	solid joints	butt joints -- pitting, material loss, hardness
Structural Metals (1) rotor forging (2) copper current collector (3) housing	solid	pitting, hardness, "C" rings (induced stress)
Cooling Fluid Wemco C	liquid	coking, color change

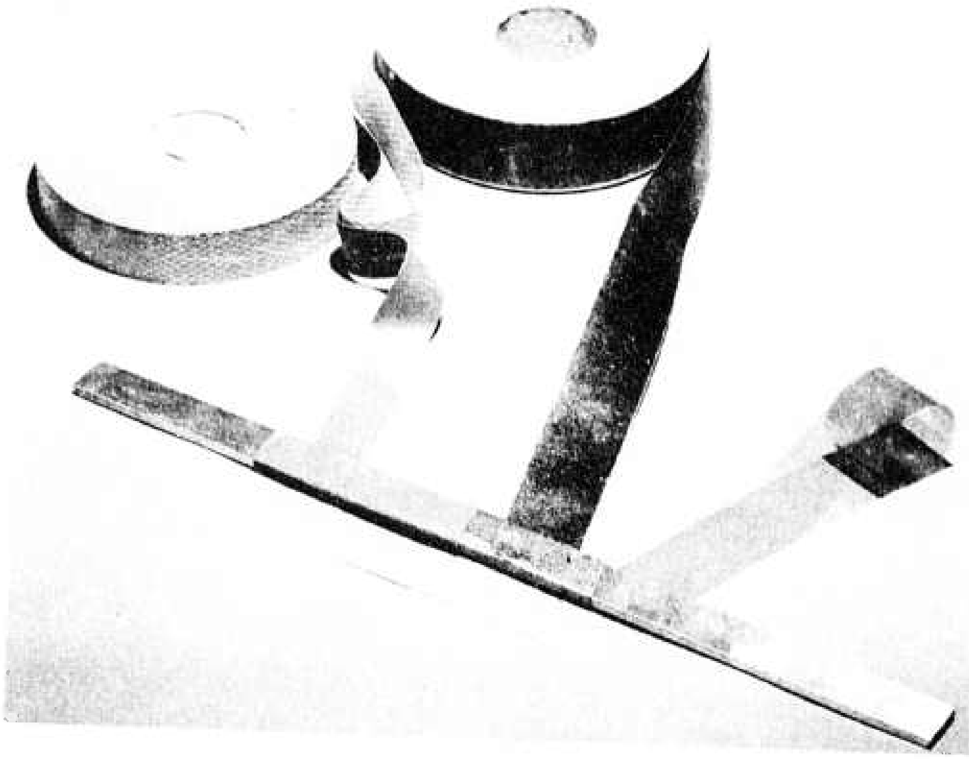


Fig. 5-1— Preparation of rotor bar insulation for NaK compatibility studies

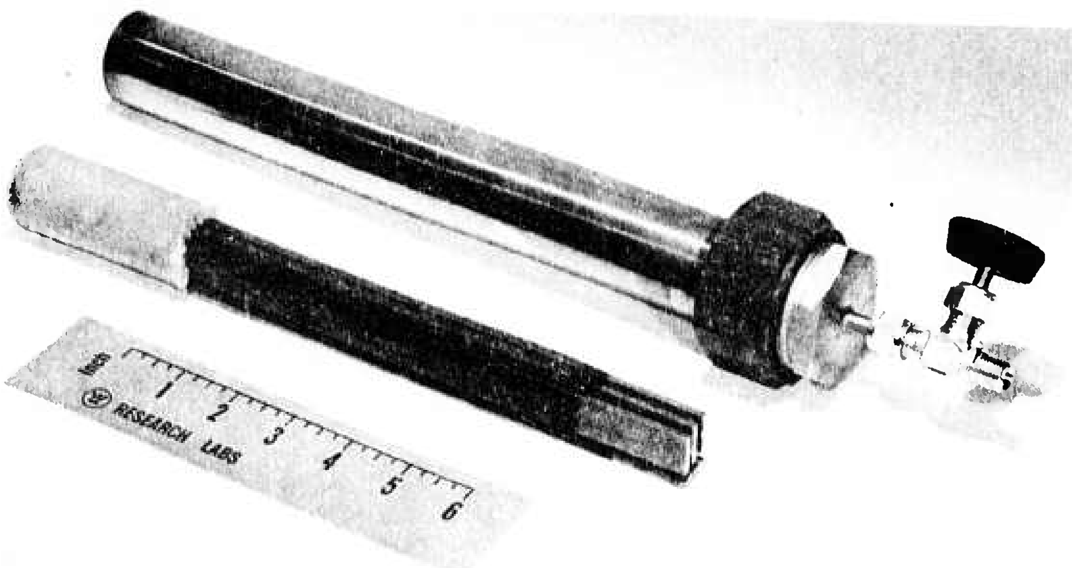


Fig. 5-2— Insulation test specimens and test canister

materials listed in Table 5-1 have been screened for NaK compatibility. Only two show promise: Sample (10) MF 343 Bronze/Graphite and Sample (12) Boron Nitride + 3 w/o Boric Oxide. The Sodium-NaK Engineering Handbook notes that potassium readily formslamellar compounds with graphite, in which the alkali metal is believed to be loosely bonded between parallel graphite planes.[2] On the other hand, high density graphite is said to be compatible with NaK to temperatures of 100°C.[3] Our preliminary running experiments in which candidate materials are exposed to NaK at room temperature, see Figure 5-3, have shown that Graphite and seal materials containing WSe_2 and Gallium Indium are not compatible with NaK. Degradation of these types of seal materials in NaK at 25°C has occurred in time periods ranging from instantaneous to > 100 hours. It is interesting to note that pure WSe_2 ignites and evolves purple smoke immediately when contacting NaK. Conversely a seal material made up of 80 w/o WSe_2 and 20 w/o Gallium/Indium survived 19 hours.

Examples of incompatible high density graphite seal materials are shown in Figure 5-4. A pyrographite material [Table 5-1 (14)] is shown in Figure 5-4a. This material survived in the NaK environment for a period of 120 hours and failed by delaminating. Figure 5-4b is an example of a high intensity ATJ graphite [Table 5-1 (19)] which completely disintegrated within a period of 35 minutes. Only one exception has been noted for graphite containing seal materials and that in the MF 343 Bronze/Graphite which appears to be compatible in NaK at room temperature. Additional studies are planned at elevated temperatures.

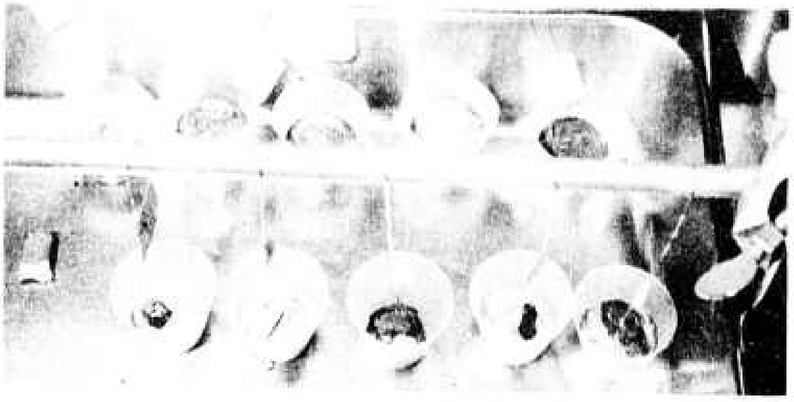
A literature survey was conducted to select braze materials that might be compatible with NaK. This study indicated that soft solder and precious metal brazes are not compatible. Nicrobraze alloys have been shown to be compatible with the NaK environment and are recommended for long term use. Since it would be highly desirable to utilize lower melting point braze alloys, a technique is being evaluated to render soft solder and previous metal brazes compatible with NaK. Test specimens have been prepared utilizing these joining alloys. The joints have been electroplated with copper or copper plus nickel to serve as a protective barrier against the NaK. Preliminary compatibility studies, performed at room temperature, showed that these plated joints were compatible with NaK. Additional studies are planned at elevated temperature which are more prototypic of actual machine conditions.

The results of the materials compatibility studies have had a direct influence on the design of the prototype SEGMAG machine and on the materials selected for machine application.

5.2.2 Liquid Metal Loop and Cover Gas Systems

Extended operation of a current collector utilizing liquid metal contacts requires a means for maintaining purity of the liquid and for replacing

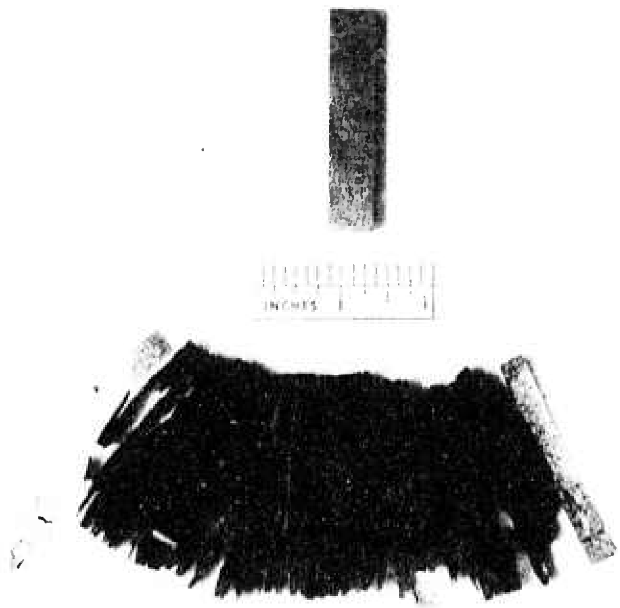
5-3a. Test Specimens



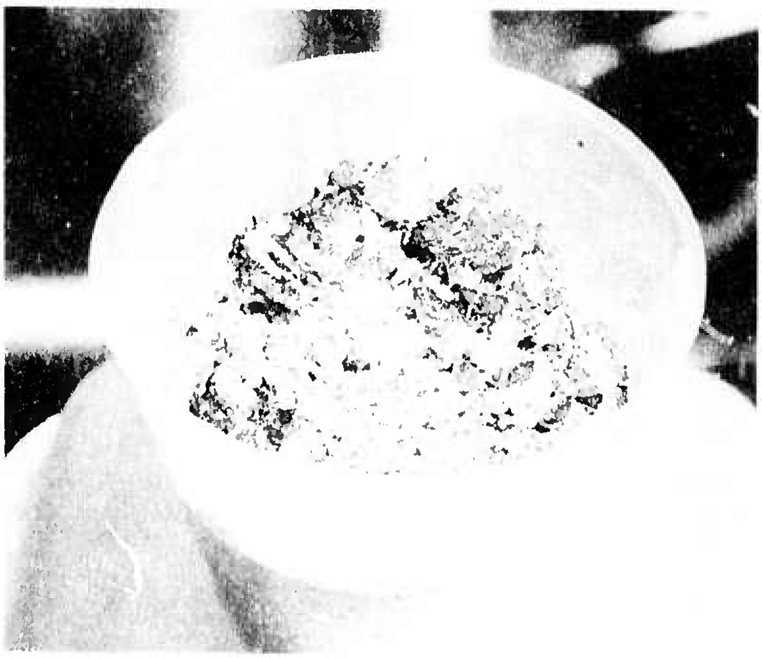
5-3b. NaK Exposure

5-3c Incompatible Seal Materials Containing Gallium/ Indium and W Se_2

Fig. 5-3—Room temperature screening of seal materials



5-4a. Pyrographite (LEM-1) Before and After NaK Exposure



5-4b. ATJ Graphite after NaK Exposure

Fig. 5-4—Incompatible graphite seal materials

any lost through aerosol formation and overflow. An external liquid metal loop system and a recirculating cover gas purification system best serves these purposes.

Present design concepts for the liquid metal (NaK) system provide for purification of the fluid by cold trapping as it is continuously recirculated through the current collectors and the loop. Makeup liquid is automatically supplied from the sump reservoir which is equipped with level sensors for indicating NaK inventory. Simplification of the liquid metal system by batch loading is a long term objective. However, the initial work must have full flexibility regarding liquid metal cleanup.

The current collector/liquid metal system for the SEGMAG generator has undergone considerable evolution as machine requirements have become better defined. A common liquid metal loop system has been designed which can supply the current collectors with NaK from six parallel NaK flow branches. This design features a single pump with contamination control and monitoring equipment in the common loop, and provisions for bypassing the demonstration machine for initial startup and conditioning of the NaK. Flowrate to individual current collectors, as well as the main flow, plugging meter flow and bypass flow, can be monitored. Flow control valves and pump power control provide a means for fine tuning the loop circuit. Dual purification stations allow maximum flexibility and contamination trapping capacity. Figure 5-5 schematically illustrates the design.

Power loss analysis in the common loop design due to the electrical shorting of the NaK lines connected to a common header and the resultant heat generated in these lines have indicated that the losses from this source are unacceptable. Two approaches were investigated to eliminate this problem of power losses. One approach was either to break each NaK line electrically or to increase its resistance in order to minimize losses. Figure 5-6 illustrates two of the methods that were experimentally tested and which demonstrated considerable promise. One technique involves the injection of gas bubbles into the NaK stream as it flows through an insulated pipe section. The other technique involves breaking the NaK into droplets as it strikes a splash plate. These techniques have been experimentally verified to be effective over more than 100 hours of operation.

A second approach to the power loss problem is to service each of the six current collectors with an independent system. A loop system based on this concept has been designed and is schematically presented in Figure 5-7. Each loop is composed of a sump tank, pump, cold trap, flow meter, valves, and piping to complete the flow system. Flowrate is controlled by flow control valves and monitored by the EM flowmeter. NaK makeup is provided by the sump tank inventory which is monitored by liquid level sensors. Purification is achieved in two stages. NaK oxides are trapped in the sump tank as they float to the surface and the cleaner liquid is drawn off below. More soluble contaminants are precipitated and filtered in the cold trap. Also included in the scheme is a positive gas flow through the NaK

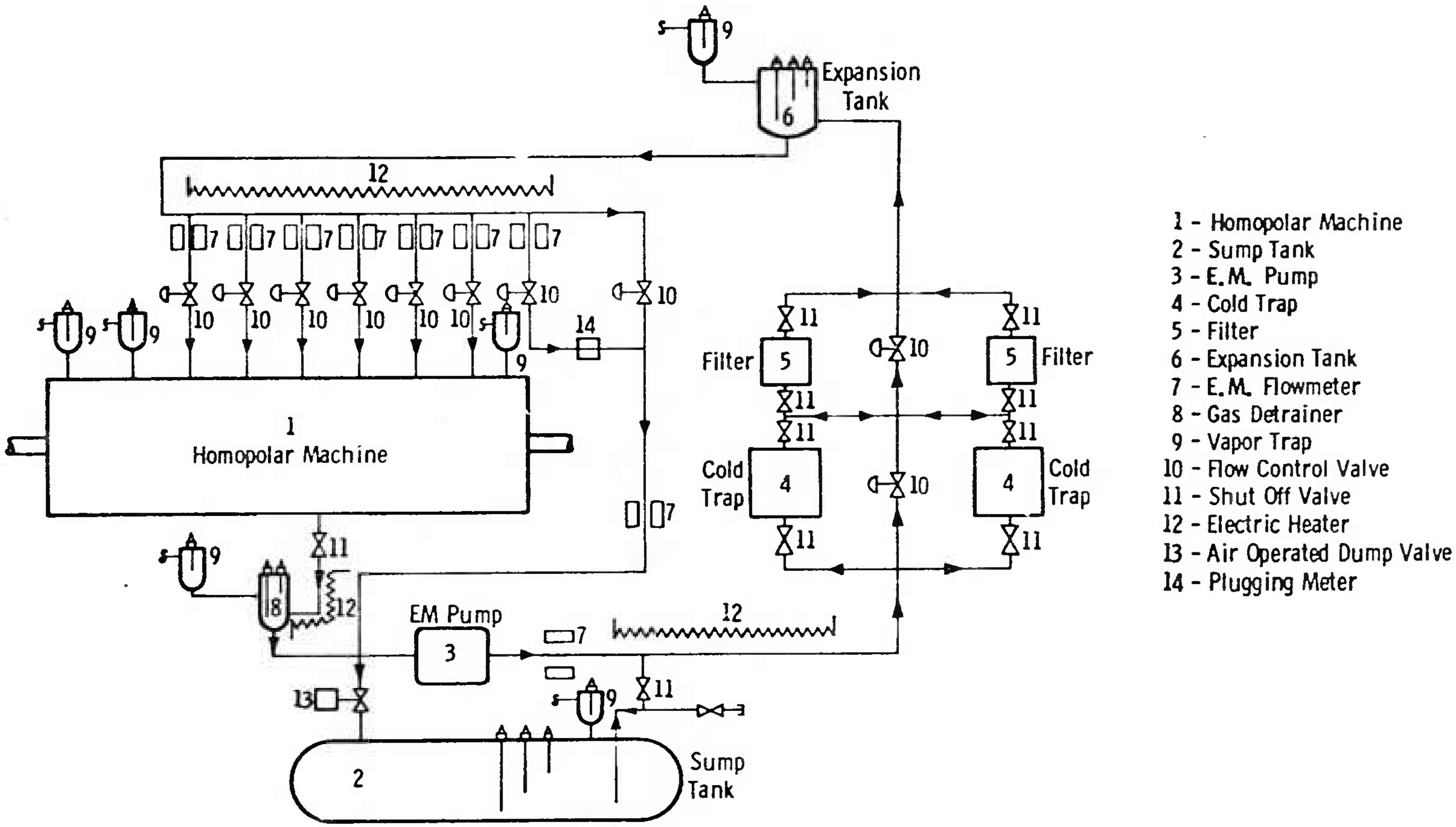
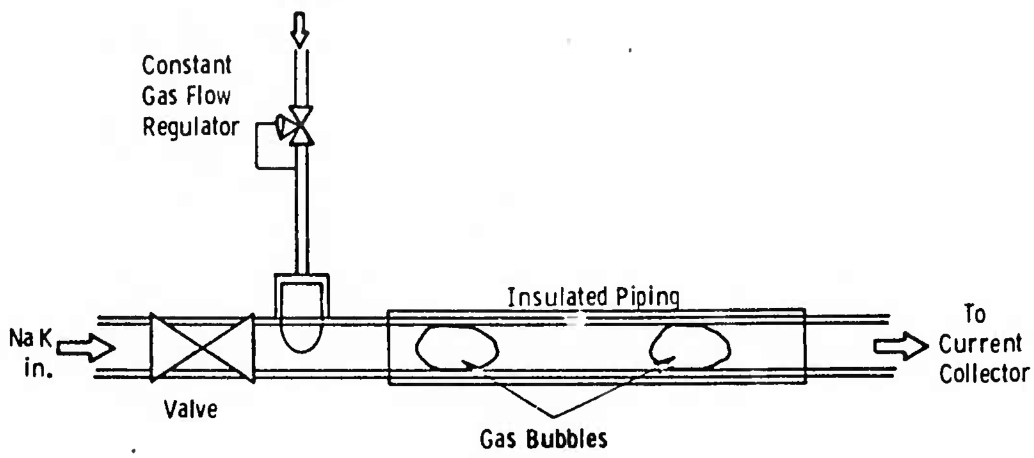
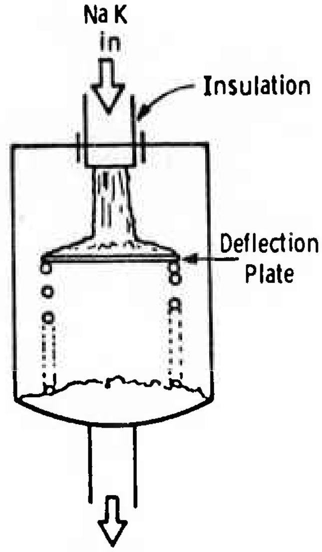


Figure 5-5 -- Common NaK Loop System for Prototype Segmag Generator



A–Gas Bubble Injection



B–Splash Plate Technique

Figure 5-6 — Two methods with experimentally demonstrated capability to break the electrical conductivity of the NaK flow.

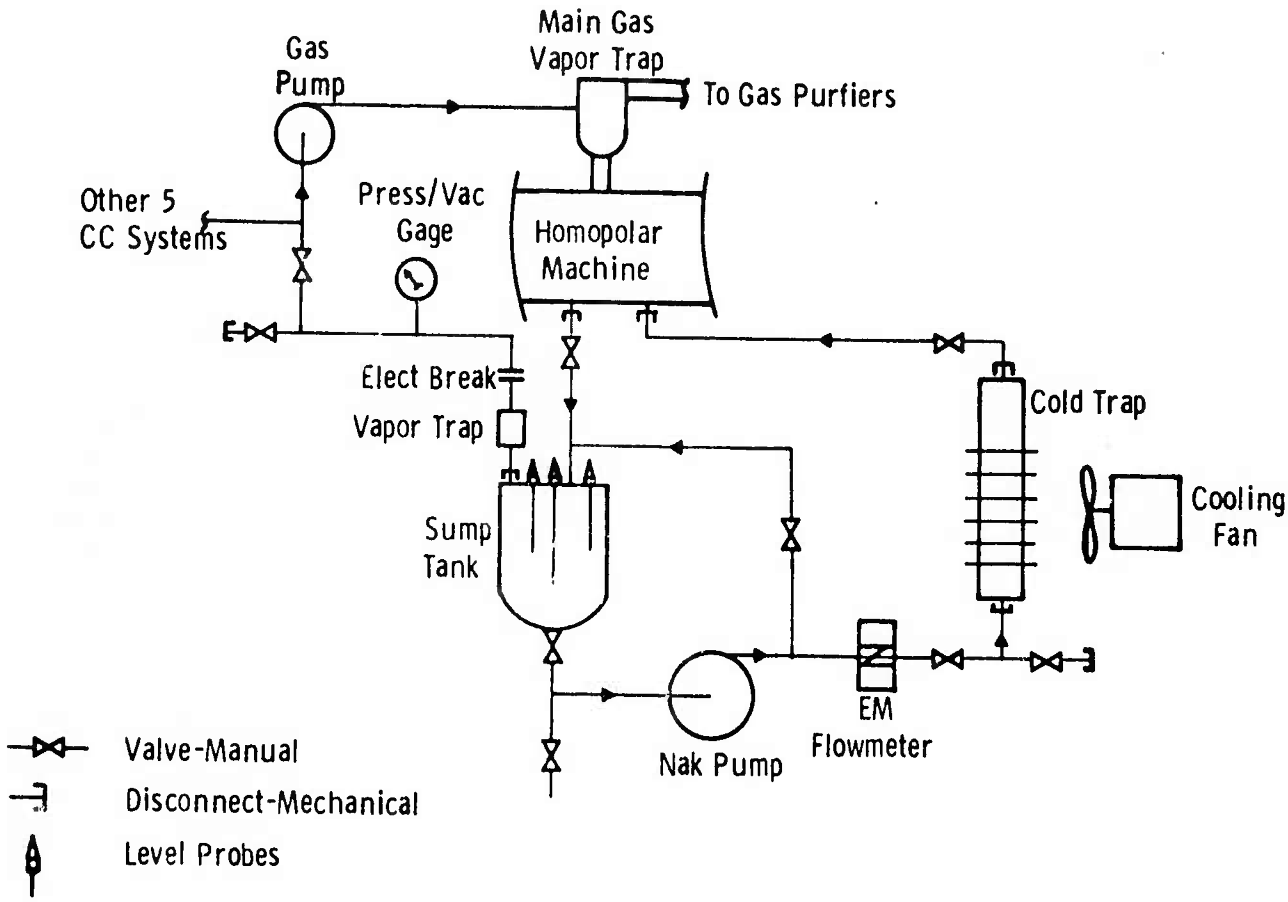


Figure 5-7 — Small loop concept to service each current collector independently.

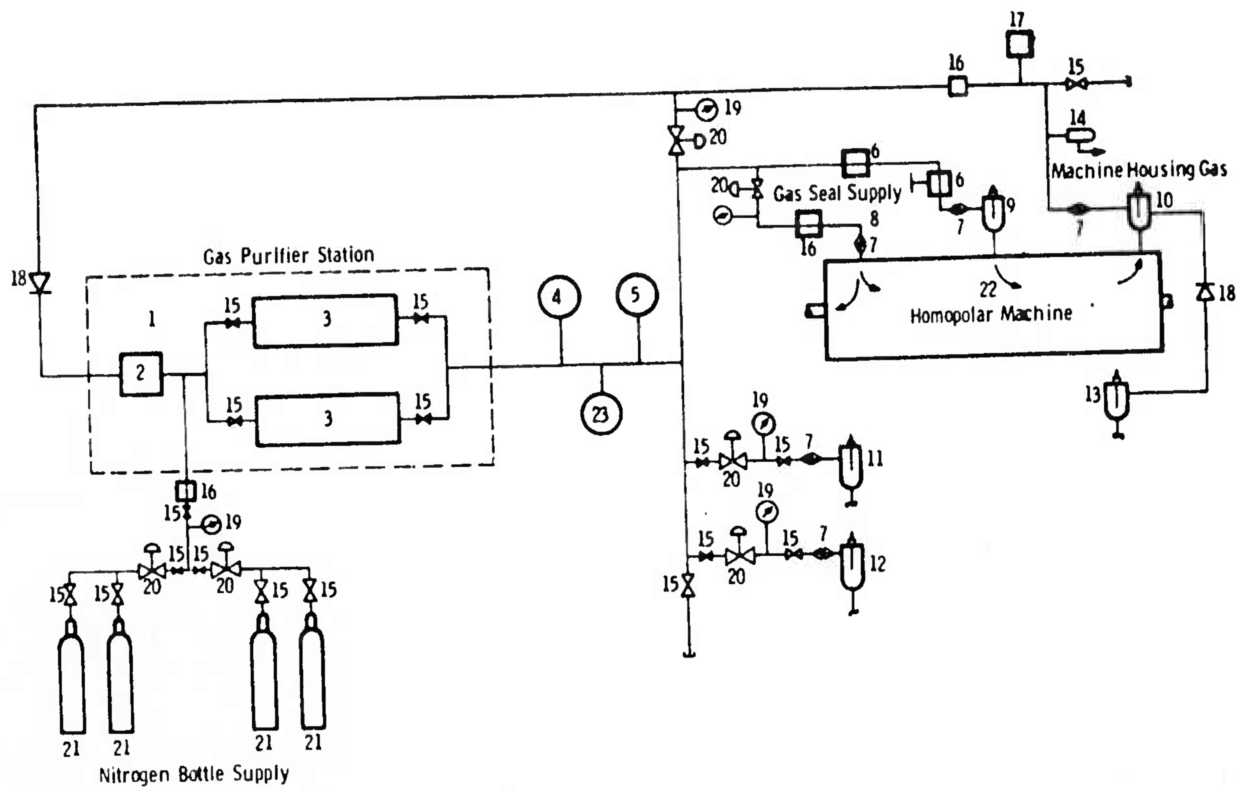
drain lines to assist draining. Success of the small independent loop concept depends upon evaluating and qualifying a suitable pump. Sealless centrifugal, canned motor, metal diaphragm, gear, and electromagnetic pumps are under consideration. The most promising pump system at this time is a commercial stainless steel, canned motor, magnetically coupled, centrifugal pump. Cost considerations as well as performance are major criteria for the selection of a suitable pump system.

An inert, protective cover gas system is required to prevent NaK oxidation and contamination products from affecting machine operation. A commercial gas recirculation and regeneration system to remove oxygen and moisture from the nitrogen cover gas has been ordered. This commercial gas recirculation unit has two parallel purification towers to permit regeneration of one tower while the other is on-line. This unit is similar to those used on inert gas glove boxes at the laboratory, and will be capable of gas recirculation at 1 ppm oxygen and moisture purification, at up to 40 cfm. The total cover gas system for the demonstration machine, tandem circumferential gas seals, and NaK loop system has been designed and is illustrated in Figure 5-8.

5.2.3 Loop and Support Studies

Several areas of investigation were pursued in order to support technically the liquid metal loop design and its subsequent operation, and to assist in the current collector development program. These areas included refinement of NaK flowrate measurement techniques; projecting NaK loop contamination rates and cold trap designs to maintain NaK purity; investigation of methods to monitor the NaK liquid level in the current collector during machine operation; analysis of possible machine decontamination techniques and sequences, with high standards of safety; and studies of the aerosol effect and methods to eliminate or control its influence upon machine operation. In addition to these activities, the test layout, instrumentation installation, and test stand assembly for the current collector test station were conducted.

If NaK flowrates through the prototype machine current collector zones are not monitored, loss of flow due to plugging or loss of NaK could have serious effects. Several methods of flowrate monitoring, such as turbine wheel, calorimetric, acoustic, pressure sensor, and electromagnetic (EM) means were reviewed[4,5,6] Design simplicity, economic operation, minimsal instrumentation (electronics), and durability were the prime considerations for the selection of EM techniques. A small commercial 1800 gauss "U" magnet was modified by pole pieces to reduce the gap across the NaK loop tubing and resulted in a 9000 gauss field. NaK flows of 50 to 500 cc/min were recorded on a recording millivoltmeter. Loss of flow actuates a relay to signal an alarm or remedial action. The prototype machine NaK flows will be monitored by such a flowmeter, with relay interlocks for safety.



1 - Automatic Regenerative Gas Purifier Station
2 - Gas Pump
3 - Gas Purifier Towers
4 - Moisture Analyzer
5 - Oxygen Analyzer
6 - Constant Flow Regulator
7 - Electric Isolator
8 - Gas Bearing Inlet
9 - Current Collector Vapor Trap
10 - Machine Housing Vapor Trap
11 - Expansion Tank Vapor Trap
12 - Sump Tank Vapor Trap
13 - Gas Detrainer Vapor Trap
14 - Pressure Relief Valve
15 - Shut Off Valve
16 - Flowmeter
17 - Pressure Alarm
18 - Check Valve
19 - Pressure Gage
20 - Pressure Regulator
21 - Nitrogen Bottles
22 - Prototype Segmag Machine
23 - Combustable Gas Detector

Figure 5-8 — Cover gas system for demonstration machine.

A NaK loop cold trap for NaK purification, either intermittent (batch process) or continuous, was designed and constructed. NaK properties[2] as well as expected machine operating conditions (cover gas recirculation rate, purity, NaK temperatures, NaK dwell time in the current collector etc.) were employed to conservatively design[7,8,9] a cold trap for 6 months operation. This acitivity will continue with cold trap efficiency experiments and operating characterization.

The in-situ monitoring of NaK liquid levels in the current collector appears feasible with acoustic probes. Initial tests with acoustic reflection techniques were promising, but were suspended pending resolution of the current collection geometry.

Machine decontamination techniques such as the conventional moist argon, dry steam, wet steam, alcohol, and water sequence as well as techniques such as liquid ammonia flooding continue to be investigated. Important to these operations are the requirements of machine material compatibility with decontamination solutions and products, in-situ decontamination (factory location or shipboard), and machine and personnel safety. Close coordination with machine design personnel is required in order not to preclude decontamination alternatives by design limits.

Initial rotor/stator experiments demonstrated the existance of a fine (NaK) aerosol mist at low rpm. Charged plates appeared effective in collecting the aerosol. Since the aerosol deposition upon exposed surfaces was not line-of-sight, more than shields or baffles will be required to resolve this problem. Experiments were designed for the high rpm current collector test stand and include cover gas flow deflection of aerosols, current collector stator/rotor gap reductions to limit the aerosol window, and withdrawalof cover gas through the NaK current collector effluent sump. These tests are considered more amenable to the stringent geometry requirements of the prototype machine than the charged plates described earlier.

Figure 5-9 illustrates the glove box test facilities where the material compatibility screening and loop support and equipment evaluation studies are being performed.

Instrumentation requirements for the current collector test stand were defined, instrument panels and layouts were determined and assembly of the test stand is underway (Figure 5-10). As illustrated, the current collector test stand will be located in a controlled, inert gas glove box with the drive motor, coolant loop, and NaK loop located below the box. The instrument panels are under assembly and include: (1) Two 24-point recorders for temperature monitoring of the current collectors, seals, bearings, and NaK loop; (2) Spark plug probes to determine NaK levels in the loop sump; (3) EM flowmeter and single point recorder for monitoring NaK flow, with alarm relay for loss of flow; (4) Drive motor controls; (5) Motor rpm monitor (by tachometer generator) with overspeed controls and relays; (6) Lebow torquemeter to determine power losses;

Figure 5-9 -- Inert cover gas glove boxes for NaK loop development and materials compatibility studies.

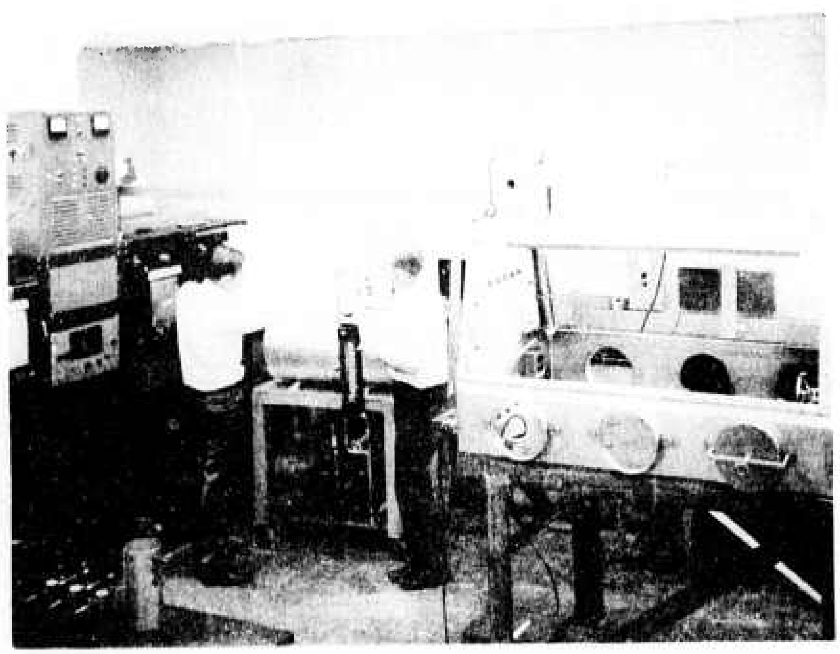


Figure 5-10 -- Current collector test stand and instrumentation in assembly.

(7) Coolant loop flowmeter, pressure gauge, loss of coolant, (i.e., over temperature) alarm; (8) Excitation coil current supply and controls; (9) Gaussmeter for magnetic field intensity; (10) NaK loop pump, cold trap, heater controls; and (11) Recirculation cover gas system and controls. Most of this instrumentation will transfer directly to the demonstration SEGMAG machine.

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SECTION 6

SEAL STUDY

6.1 OBJECTIVES

The primary goal of this task is to develop a method to avoid contamination of the machine's containment vessel by either air or the hydrocarbon-based fluid used for bearing lubrication and thereby prevent contamination of the liquid metal system. In addition, excessive losses of the machine's inert cover gas to the atmosphere must be avoided.

The specific objectives of the seal task of this program are as follows:

- Construct a seal test stand capable of evaluating the performance of tandem circumferential seals in a dry, inert environment.
- Perform functional seal tests at 3600 rpm in dry nitrogen gas on seal units equipped with carbon-graphite type materials capable of retaining their self-lubricating ability in a no-moisture environment.
- Perform functional endurance tests on that combination of seal design and material demonstrating optimum performance with respect to gas leakage, seal wear, operating temperature, and NaK compatibility.

Complementing this portion of the program are two supporting efforts designed to (a) evaluate the compatibility of a variety of candidate seal materials with NaK (reported in 5.2.1), and (b) determine the friction-wear characteristics of these seal materials.

6.2 PRIOR AND RELATED WORK

Studies performed during the Phase I effort of this program indicated strongly that a tandem circumferential seal,[1,2] or bore seal, is the prime candidate for satisfying the requirements imposed on the rotor shaft seal. The circumferential seal not only exhibits the ability to withstand high velocity rubbing at its primary sealing surfaces, but also the ability to provide a high degree of sealing effectiveness. Its design conserves weight and space, provides virtually unlimited shaft travel, and is easily assembled. The seal ring itself is enclosed by a cover ring to close off joint leakage. Joints on the seal and cover ring segments are staggered to minimize leakage at these locations. The segments are usually held in place by Inconel X garter springs.

The runners against which the seal operates are made as replaceable shaft sleeves of hard chrome plate or Linde flame sprayed alumina. It should be pointed out that the geometry of the runner is as important as that of the seal. It must be sealed to the shaft to prevent leakage past

itself and the shaft. Runner faces must be truly flat and should be clamped to a shaft shoulder with no distortion.

With regard to material selection for use in these seals, care must be exercised to insure that the self-lubricating composite employed retains its lubricating ability in a no-moisture, inert environment. In this respect, a recent Westinghouse supported program[3] directed toward the evaluation of seal materials for liquid metal pump cover gas systems has shown that standard grades of carbon-graphite seal materials exhibit extremely poor friction-wear characteristics in dry argon. In contrast, modification of these carbon-graphites through the addition of fillers, such as Teflon, molybdenum diselenide, tungsten disulfide, etc., has reduced sliding friction coefficients of these materials by a factor of three under identical operating conditions. Seal wear was negligible over a 100-hour period under a 6 psi load at 2200 fpm.

In view of the decision to utilize the tandem circumferential seal as the rotor shaft seal, a seal test stand was designed during the Phase I effort of this program. Figure 6-1 is a schematic of the device and provides an overall view of the drive motor, support frame, and the seal test stand itself. Figure 6-2 is a more detailed view of the test stand, illustrating slave bearing preload techniques and test seal mounting and locking arrangement. The drive motor is a 10 hp, 3 phase, 230 volt adjustable speed drive with a static dc thyristor drive control. Maximum operating speed of the motor is 3600 rpm, regulated to within $\pm$ 1% by means of a separate tachometer unit. The motor is equipped with jogging and reversing capabilities as well as dynamic braking. Through the use of a 2:1 pulley ratio, the test stand is capable of performing experiments on various seal configurations over a 7000 rpm speed range in inert, bone-dry environments. Leakage rates, operating speed, and seal temperature are continuously monitored. One major objective of this task is to construct this test device so as to provide the means for evaluating the performance of candidate shaft/containment vessel seal configurations. The test stand is capable of evaluating seals for shafts ranging in diameters from 2 to 6 inches.

6.2 CURRENT PROGRESS

The test program planned for functional seal testing consists of three phases:

1) Candidate seal materials will be evaluated regarding their ability to operate effectively in an inert, no-moisture environment.

2) Concurrently, these materials will also be evaluated with respect to their compatibility with NaK at room temperature and, where appropriate, at elevated temperature.

3) Finally, the most promising materials will be fabricated into actual seals and tested extensively with respect to operating speed, runner

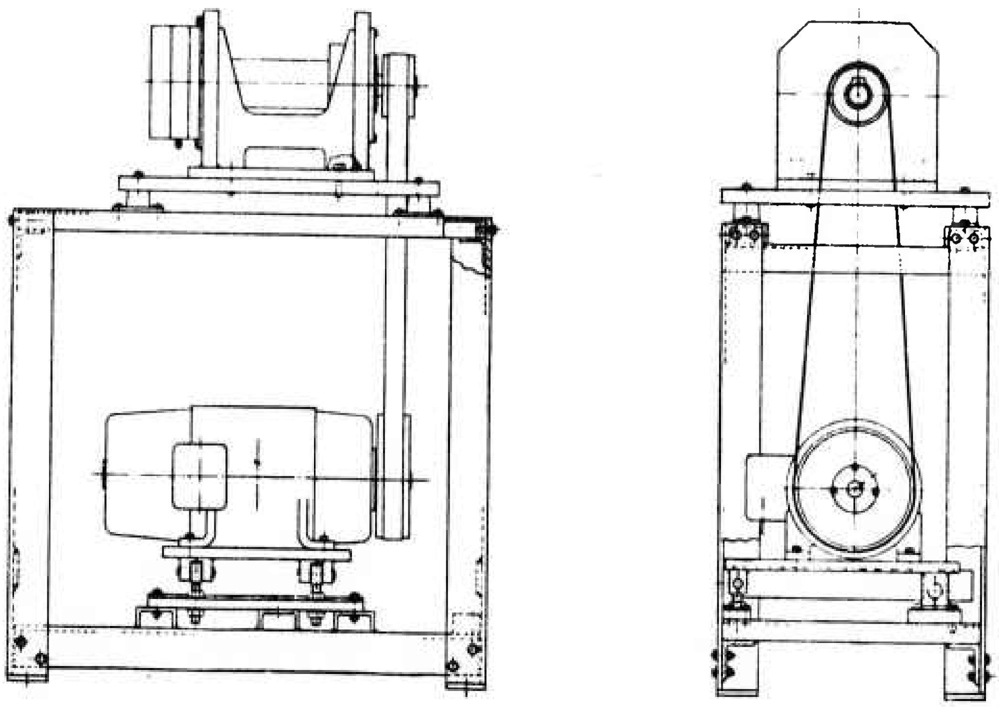

Figure 6-1 - Shaft/Containment Seal Test Stand

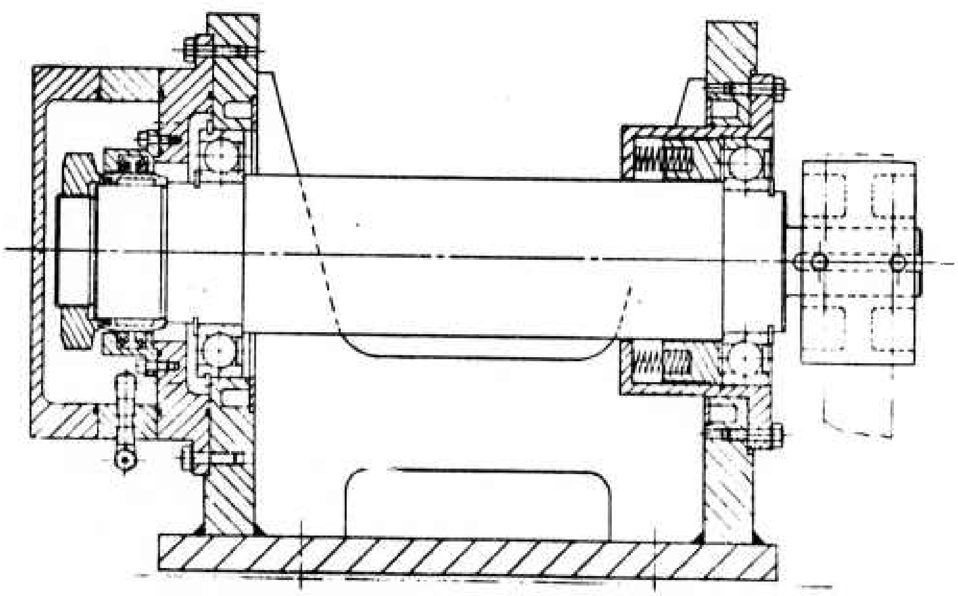

Figure 6-2 - Details of Seal Test Device

design and material, and pressure. The results will be compared against those obtained on units employing standard carbon-graphite materials. Parameters monitored during these tests will include seal water, leakage, and operating temperatures.

During this reporting period, the above program was implemented by initiating construction of the test stand and procuring candidate seal materials for evaluation with respect to friction-wear characteristics and NaK compatibility. Progress in these areas is described below.

6.2.1 Test Stand Construction

Fabrication of the seal test stand was completed during this reporting period. Figure 6-3 is a photograph of the rig and shows the main frame, seal housing chamber, spindle, and slave bearing arrangement. Drive motor delivery and installation are scheduled for early in the next reporting period.

The hardened, tool steel (#21) shaft is 3 inches in diameter at the test seal site. Precision bearings employed as slave bearings are grease packed and equipped with riveted phenolic retainers. Maximum speed rating for these bearings is 8400 rpm when grease is used as the lubricant. A sealed, plexiglas housing is located around the test seal and provides for not only visual observation of the test seal while in operating but also a means for monitoring gas leakage past the seal face. The flow rate of gas feeding the seal faces is continuously monitored. Seal temperature and both spindle bearing temperatures are also continuously monitored and recorded. A temperature excursion at any of these locations will automatically terminate the test by interrupting power to the motor.

6.2.2 Material Studies of Candidate Seal Composites

In considering carbon-graphite base materials as potential candidates for seal applications in NaK, or NaK-containing environments, materials compatibilities must be determined. As reported in Section 5.2.1, compatibility studies being performed under the Phase II effort of this program have already illustrated that many of the conventional carbon-graphites employed as seal materials undergo rapid chemical reactions with NaK at room temperature. Table 6-1 lists and identifies the various seal materials procured for compatibility studies.

As indicated in the compatibility studies, the rapid reaction of graphite with potassium presents a serious problem in respect to considering graphite composites as seal materials for NaK. In addition, the potassium may act as a "spacer" for opening the lattice for reaction with sodium. Since the reactions take place between the layer planes of graphite, the less structured carbon-graphite or carbon materials should be less

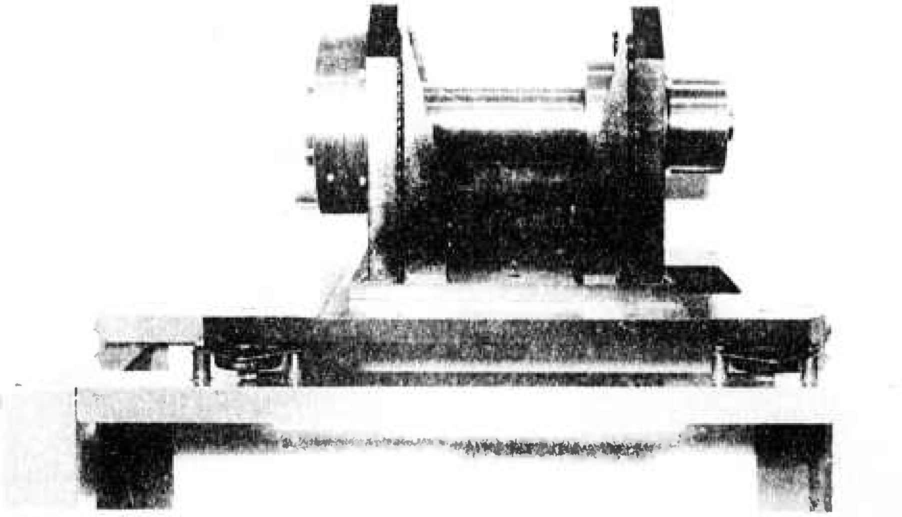

Figure 6-3 - Seal Test Stand

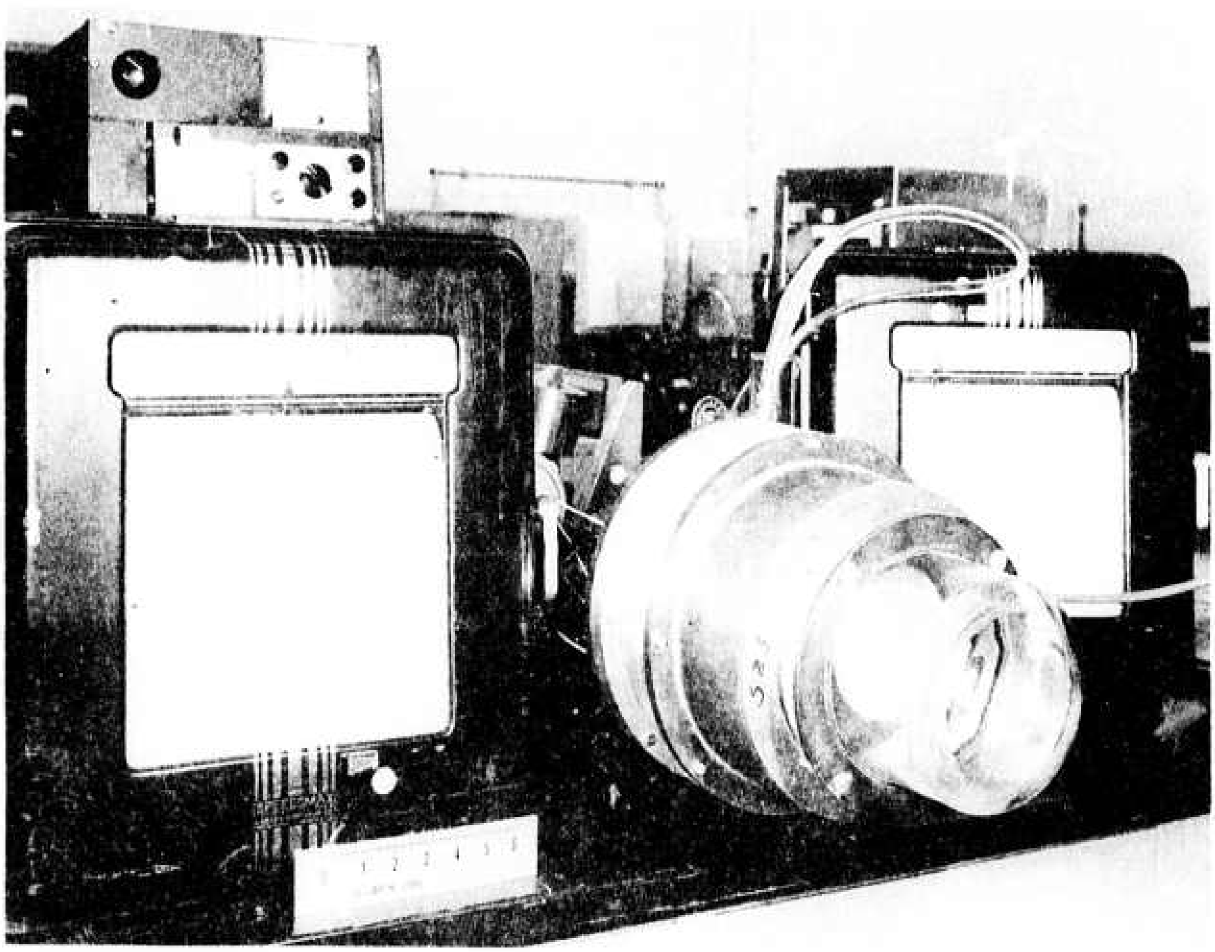

Figure 6-4 - Face Seal Test Stand

TABLE 6-1
SEAL MATERIAL PROCURED FOR FRICTION-WEAR AND COMPATIBILITY STUDIES

Grade Number	Supplier	Identification
EVC	U.S. Graphite	99.9% graphite
Sk-235	Stackpole Carbon Co.	Carbon-graphite + MoS_2
Sk-278	Stackpole Carbon Co.	Carbon-graphite + MoS_2 (>Sk-235)
Sk-218	Stackpole Carbon Co.	Similar to Sk-278 with Phenolic impregnation
CR-218	Stackpole Carbon Co.	Resin bonded with fillers of graphite and Teflon
CR-219	Stackpole Carbon Co.	Resin bonded with fillers of graphite and Teflon
1257	Stackpole Carbon Co.	Straight carbon-graphite
MF-343	Stackpole Carbon Co.	Bronze matrix + carbon
SP-3	Dupont	Polyimide matrix + 15% graphite + 10% Teflon
SP-211	Dupont	Polyimide matrix + 15% MoS_2
WGI	Westinghouse Electric	80% tungsten diselenide - 20% gallium-indium
WGI-O	Westinghouse Electric	WGI + oxide coating
WGI-A	Westinghouse Electric	90% WGI - 5% Ag - 5% CaF_2
WSe_2	Cerac, Inc.	Tungsten diselenide
AXZ	Poco Graphite	Carbon-graphite; density = 1.5 gms/cc
AXM	Poco Graphite	Carbon-graphite; density = 1.8 gms/cc
AXF	Poco Graphite	Carbon-graphite; density = 1.9 gms/cc
LEM-1	Raytheon	Pyrographite
LEM-2	Raytheon	Impervious pyroimpregnated graphite
BN-O	Raytheon	Boron nitride + 3 w/o boric oxide

reactive and may represent potential materials for "carbon" type base composite seal materials where direct exposure to NaK is involved. Composite matrices could be comprised of NaK-resistant metals or polymers, such as iron, beryllium copper, polyimide, polypropylene and polyethylene. Throughout these matrices would be distributed potentially NaK compatible solid lubricants such as boron nitride, carbon, or inorganic fluorides.

In addition to NaK compatibility studies, it is also necessary to evaluate the friction-wear characteristics of candidate seal materials to determine their ability to retain their self-lubricating properties in a no-moisture, inert environment. It is a well-known fact in the lubrication field that the solid lubricating characteristics of graphite and carbon-graphite composites are lost when moisture is removed from their environment. The rotor shaft seals of the prototype SEGMAG machine must operate effectively in the dry, inert cover gas of the machine's containment vessel. For this reason, the ability of the seal material to lubricate satisfactorily in such an environment is of major concern.

During the reporting period, two functional seal tests were completed on face seals operating in a dry, inert environment. The seals were operated at a surface velocity of 2400 fpm (40 fps) and face loadings of 15 psi and 30 psi. These operating conditions are equivalent to PV* ratings of 36,000 and 72,000, respectively; conditions substantially more severe than those anticipated for the prototype SEGMAG machine. The seal material was fabricated from the WSe_2/GaIn composite and mated with a tungsten carbide runner. After operating for a period of 140 hours, the tests were intentionally terminated and wear measurements taken. In both experiments, seal wear was found to be less than 0.5 mil. Seal operating temperature under the 15 psi and 30 psi load conditions stabilized at 105° and 110°F, respectively. Temperature stabilization required approximately 24 hours, with a peak temperature of 140°F being reached during this period. Figure 6-4 is a photograph of the equipment being used in these tests.

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*Pressure (psi) x surface velocity (fpm)

6.3 REFERENCES

1. "Dynamic Sealing: Theory and Practice," Koppers Company, Inc., Baltimore, Maryland.

2. "Mechanical Seals," Mayer, E., London ILIFFE Books LTD, 1969.

3. Bowen, P. H., "Cover Gas Seal Materials for a Liquid Metal Pump," Westinghouse Research Report 73-1B6-PUMAT-R1.

SECTION 7
PLAN FOR PHASE II

7.0 OBJECTIVES

A plan for Phase II of the Contract has the primary objective of providing the necessary theoretical and engineering design work, as well as the supporting experimental tasks, to develop reliable and efficient subsystems necessary for the successful operation of segmented magnet homopolar machines, such as generators, motors, and torque converters. Another objective is to identify the key task areas, along with subtask activities, necessary to the design, construction, and operation of a SEGMAG machine by the end of Phase II.

The test plan for Phase II of the ARPA Contract to develop a prototype SEGMAG machine is divided into five major task areas:

- Fundamental Studies
- Current Collection Development
- Seal Studies
- Liquid Metal and Cover Gas Systems, including Materials Compatibility Studies
- Machine Design and Testing

7.1 PRIOR AND RELATED WORK

This is fully reported in sections 1 to 6 of this report

7.2 CURRENT PROGRESS

This is fully reported in sections 1 to 6 of this report.